1974

The development of a self-adaptive procedure for the economic improvement of cutting conditions /

Robert J. Johnson
Lehigh University

THE DEVELOPMENT OF A SELF-ADAPTIVE PROCEDURE FOR THE ECONOMIC IMPROVEMENT OF CUTTING CONDITIONS

by

Robert J. Johnson

A THESIS

Presented to the Graduate Faculty

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Industrial Engineering

Lehigh University
1974

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements of the degree of Master of Science.

Sept 19 1974
Date

Professor in Charge

Head of Department

Acknowledgements

At this time I would like to thank Professor Mikell P. Groover for his thoughts and guidance during the research. I am very appreciative of his project leadership and assistance to me throughout my graduate study at Lehigh University.

I also wish to express my gratitude to the National Science Foundation which sponsored the research on which this thesis was based.

Thanks are also due Mr. Gilbert Zambelli, the technician of the Manufacturing Processes Laboratory. Throughout the machining phase of the project his technical assistance was invaluable to me.

Table of Contents

Table of Contents (cont.)

List of Figures

List of Figures (cont.)

Abstract

The development of a self-adaptive procedure for the improvement of cutting conditions in metal machining is reported in this thesis. The procedure was examined through the use of computer simulation and by actual machine shop testing.

The results demonstrate how an optimum-seeking search technique can be applied to a turning operation to economically improve cutting conditions as specified in machining handbooks. Improvement of cutting conditions was considered to be a change in speed or feed which resulted in a more desirable level of an index of performance of the process. The computer simulation and machine shop validation phases of the research showed that the method of steepest descent, a gradient search technique, was able to substantially improve a turning operation in which minimizing cost was the primary interest.

In order to realistically "optimize" cutting conditions, it was understood that a limited range of speeds and feeds exists which can be feasibly searched by such a self-adaptive procedure. Machine and tool capabilities and product requirements constrain the range of search. It was found that the self-adaptive procedure should be constrained to operate within machine and tool limitations. A penalty cost for exceeding product requirements, specifically surface finish specifications, was investigated and found to perform well in the computer simulation. Additional study is needed to apply such a cost to actual operation.

Introduction

Due to the tremendous number of products formed by metal cutting processes, economical machining and improved productivity is of great importance. Improved productivity in metal machining operations can be obtained in several ways.[1]

1) Efficient utilization of the machine tools obtained by minimizing the down-time at each machine. An example of this approach is the N/C tool which employs optimized tool paths, automatic cycling, and automatic tool changes.

2) Utilization of improved cutting tools capable of longer tool lives and improved metal removal rates.

3) Optimization of the actual machining phase of the operation in which the tool is engaged in the workpiece and is removing metal. This method necessarily involves the optimization of machining conditions on the basis of some index of performance such as minimum cost per piece maximum production rate, or maximum profit.

The objective of this research was to investigate the third alternative of increasing productivity by improving cutting conditions with respect to a desirable economic index of performance. Many analyses of the topic have been made employing mathematical optimization techniques to arrive

---

[1] M.P. Groover and R. J. Johnson, "Alternative Methods for Determining Optimum Machining Conditions," SME Technical Paper MR74-203, p.1.

at the "best" set of cutting conditions with respect to the index. Such analyses fall under the heading of classical or traditional machining economics and suffer from an inability to respond to the variability known to be present in metal cutting.

The research proposed in this study attempts to develop a means of dealing with variability by searching for the "optimum" set of cutting conditions with respect to an index of performance on a response surface containing the uncertainty found to occur in the machining operation. The method developed here is intended for use in a self-adaptive system which is capable of adjusting cutting conditions in a varying environment to improve the index of performance. Acutal machining data is used to determine the range of variability one could expect in the measurement of the important process variables needed to evaluate the index of performance. Such a method was initially tested by Monte Carlo computer simulation using probabilistic models of the important process variables, such as flank wear and surface finish, instead of actual machining measurement. Computer simulation provided an excellent means of testing the models, economic calculations, and the search method required to improve cutting conditions with respect to an index of performance. Once the computer testing was complete, the search method was applied to actual machining and alterations were made on the basis of results found through in-shop testing. Before this method can be described fully, an understanding of the machining economics problem and previous analyses of the problem is essential.

Traditional Machining Economics

One of the earliest analyses of machining costs was made over 60 years ago by F. W. Taylor in his now classic research paper, "On The Art of Cutting Metals". In this work, Taylor proposed a "tool life equation" still widely used today. Taylor recognized a power relationship between cutting speed and tool life.

$$VT^n = C$$

where

V = cutting time in SFPM

T = tool life in minutes

n = slope of the log-log plotted linear relationship between tool-life and speed.

C = constant

Tool life can be defined in several ways:

1) Total destruction of the tool
2) A level of flank wear on the tool, e.g. .040".
3) The time at which the tool no longer produces useful product with respect to size tolerance and surface finish

A sample of the Taylor relationship between tool life and cutting speed can be found in Figure 1. Values of the constants n and C are determined experimentally and are unique for each tool-work material combination.

Tool life and the associated costs involved in replacing or resharpening a worn tool are a significant component of the cost of metal machining. Thus, the development of the Taylor relationship to predict tool life is an important development. However, rather important difficulties exist which seriously restrict the accuracy of tool life prediction by the Taylor equation.

1) Tool life depends not only on speed but on feed, depth of cut, tool material properties, work material properties, and tool geometry.[2] Although, in most cases, speed is the most significant variable, others often need consideration. Feed can be seen to have a substantial effect on tool wear and life in Figure 2, suggesting the need for an expanded Taylor equation including feed rate. Such expanded equations have been proposed and are of the form:[3]

$$VT^a f^b = D$$

where

f = feed rate in inches/rev

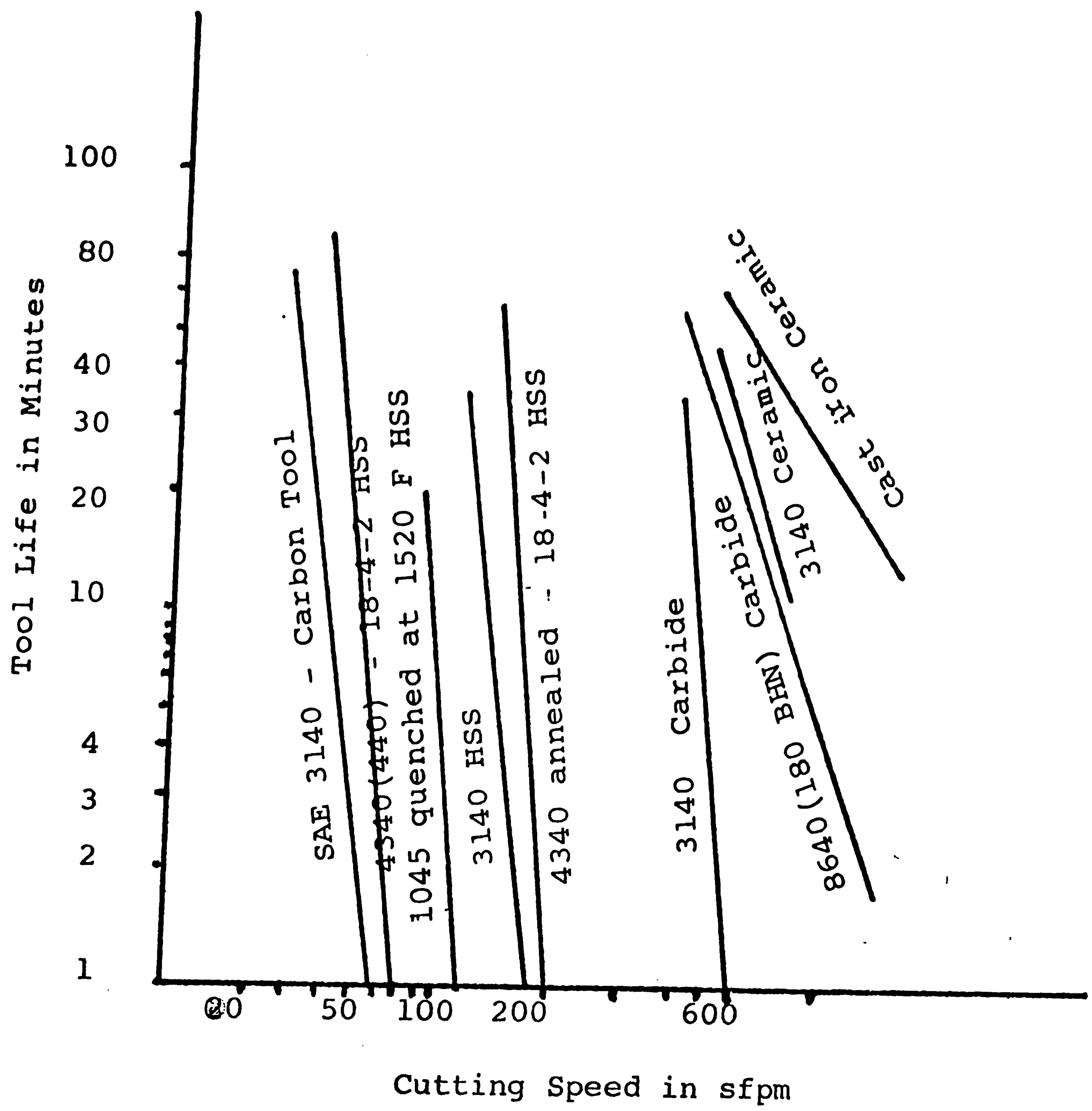
a, b, D = experimentally determined constants

---

[2] J.P. Vidosic, Metal Machining and Forming Technology, p. 421.

[3] Nathan H. Cook, Manufacturing Analysis, p. 67.

TOOL LIFE CURVES



Adapted from :
Vidosic, Metal Machining and Forming Technology, p. 420.

Figure 1

TOOL LIFE VS CUTTING SPEED CURVE

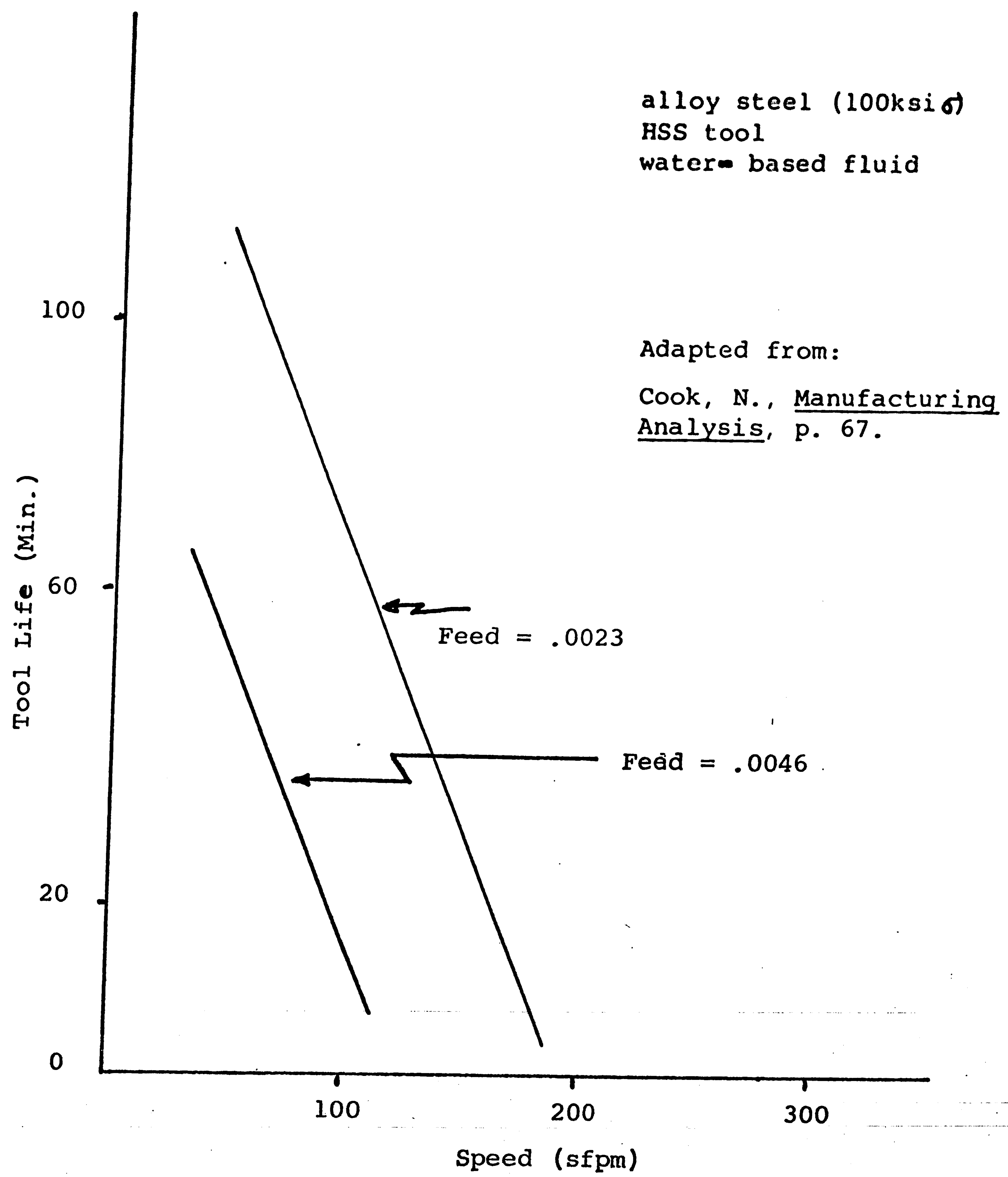


Figure 2

2) The Taylor relationship assumes that the end of the life of a tool is precipitated by "normal wear" due to "shearing of metallic junctions".[4] This normal or abrasive wear is predictable within a certain range of "moderate" cutting conditions and this relationship between flank wear and time can be seen in Figure 3. Notice in Figure 3 that a period of break-in wear occurs initially followed by wear at a nearly constant rate. Near the end of the life of the tool an accelerated wear period occurs which is not easily predicted. Apparently, a different wear mechanism occurs in this accelerated region, possibly related to temperature or rupture failures. The inapplicability of the predictable normal wear model suggested by the Taylor equation at "non-moderate" cutting conditions can also be explained by this consideration of other wear mechanisms.

3) It has been found that the constants utilized by Taylor's equation are not always constant. It might be suggested that the equation does not include enough factors or is an incorrect formulation. However, it is more reasonable to assume that the Taylor equation is as "correct" as any deterministic equation describing a probabilistic relationship could be. It has been seen by experimental metal cutting that "the tool wear mechanism, although functionally related to cutting conditions and material, is a random

---

[4] J. P. Vidosic, p. 424.

Flank Wear vs. Cutting Time Relationship

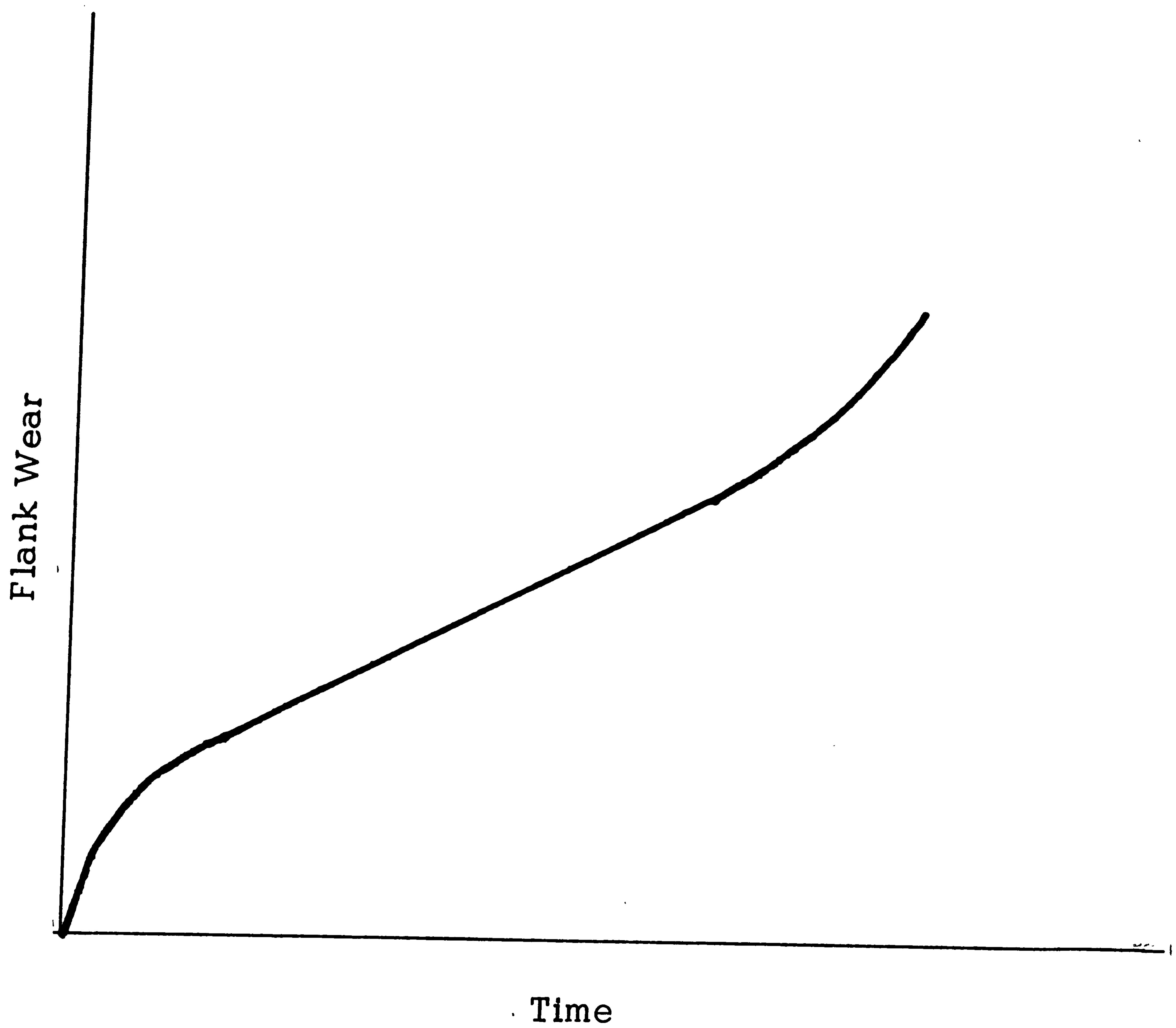


Figure 3

process."[5] This fact is reflected in actual production cutting by the variation seen in tool life of tools used under identical cutting conditions. Thus, at best, a deterministic equation can only describe the tool life relationship for the average case.

As will be now shown, the tool cost is one of several components of machining cost. However, it is a significant component. The traditional machining economics models predict tool life by use of the unexpanded, speed only Taylor relationship. the following assumptions are generally made to overcome some of the difficulties mentioned.[6]

1) Taylor's equation is valid in the range of cutting conditions considered. In other words, in the range of cutting conditions considered, "normal" tool wear occurs according to the model of Figure 3.

2) The constants n and C are constant.

These assumptions may or may not be feasible.

Machining Cost Analysis

In any type of metal machining, the total unit cost to produce the workpiece consists of two components.[7]

1) Non productive costs involving the costs of machine operation and overhead during loading, advance, return, and unloading and during

---

[5] M.P. Groover, "Computer Simulation of The Machining Economics Problem," Lehigh University, p.5.

[6] M.F. DeVries, "Machining Economics," ASTME Paper No. MR69-779, pp.2-3.

[7] Vidosic, p. 325.

tool changing or sharpening.

2) Productive costs including the dollars spent for the time during actual metal removal. Essentially, this involves the labor, machine, and overhead costs incurred during cutting time plus the tool cost expended.

The basic model most often used in the study of traditional machining economics describes the cost per unit of a single point tool rough turning operation.[8] The reason for the selection of this operation for analysis is that a great amount of tool life information exists from research investigations and single point turning is a relatively simple, common operation. The basic model considers the cost per unit to be the sum of productive and non-productive components. Thus, the total cost per unit can be expressed as:

unit cost =	machining cost per piece	+	tool cost per piece		(Productive)
					+
	+ tool changing cost per piece	+	work changing cost per piece		(Non-Productive)

The machining cost per piece is equal to the cost of the operating time (labor, rate, machine overhead, etc.) , Co, in dollars per minute multiplied by the actual cutting time per piece, t_m, in minutes per piece.[9]

Machining Cost = $C_o t_m$

---

[8] DeVries, p.3.

[9] DeVries, p.4.

The tool cost per piece can be defined as the product of the tool cost per edge, C_t, in dollars per edge and the ratio of the cutting time to the average tool life, T. The ratio essentially relates how much of the tool is expended per piece. As mentioned the value of the tool life is obtained from a speed only Taylor equation.

$$\text{Tool cost} = C_t \frac{t_m}{T}$$

The third component is the non-productive cost of changing the tool. It is equal to the product of the cost of the operating time, C_o, the tool changing time, t_c, and the ratio, t_m/T.

$$\text{Tool Changing Cost} = C_o t_c \frac{t_m}{T}$$

The final cost component in the basic model is the non-productive cost of handling the workpiece. It is described by the product of the handling time, t_h, in minutes per workpiece, and the cost of the operating time, C_o.

$$\text{Workpiece changing cost} = C_o t_h$$

The sum of these two productive and two non-productive cost components defines the unit cost in dollars per unit. Thus, the basic machining economics model:

$$c_u = C_o t_m + \frac{t_m}{T} (C_t + C_o t_c) + C_o t_h$$

In the early 1950's W.W. Gilbert used this basic model to determine the "optimum" cutting speed with respect to two indices of performance, minimum cost per piece and maximum production rate. Gilbert and his predecessors, therefore, began the development of traditional machining economics which considered speed as the only independent variable. Feed rate and depth of cut were held at a constant level while speed was "optimized". The relationship between the cost per piece and its components and cutting speed can be seen in Figure 4. In Figure 4, notice that machining cost decreases with increasing cutting speed. This is true since cutting time and the costs incurred during cutting decrease with increasing speed. The following equation for the cutting time for a turning operation gives insight into the relationship between cutting time (and costs) and speed.

$$t_m = \frac{L\pi D}{12fV}$$

where

L = axial length of cut, inches

D = diameter of the workpiece, inches

f = feed rate, ipr

V = speed, sfpm

t_m = cutting time

In Figure 4, it can also be seen that increasing speed increases tool and tool changing costs. The reason for this is that "the higher the speed, the shorter the time to a given amount of wear" and thus, the shorter the tool life.[10]

---

[10] Vidosic, p. 429.

INFLUENCE OF CUTTING SPEED ON COSTS

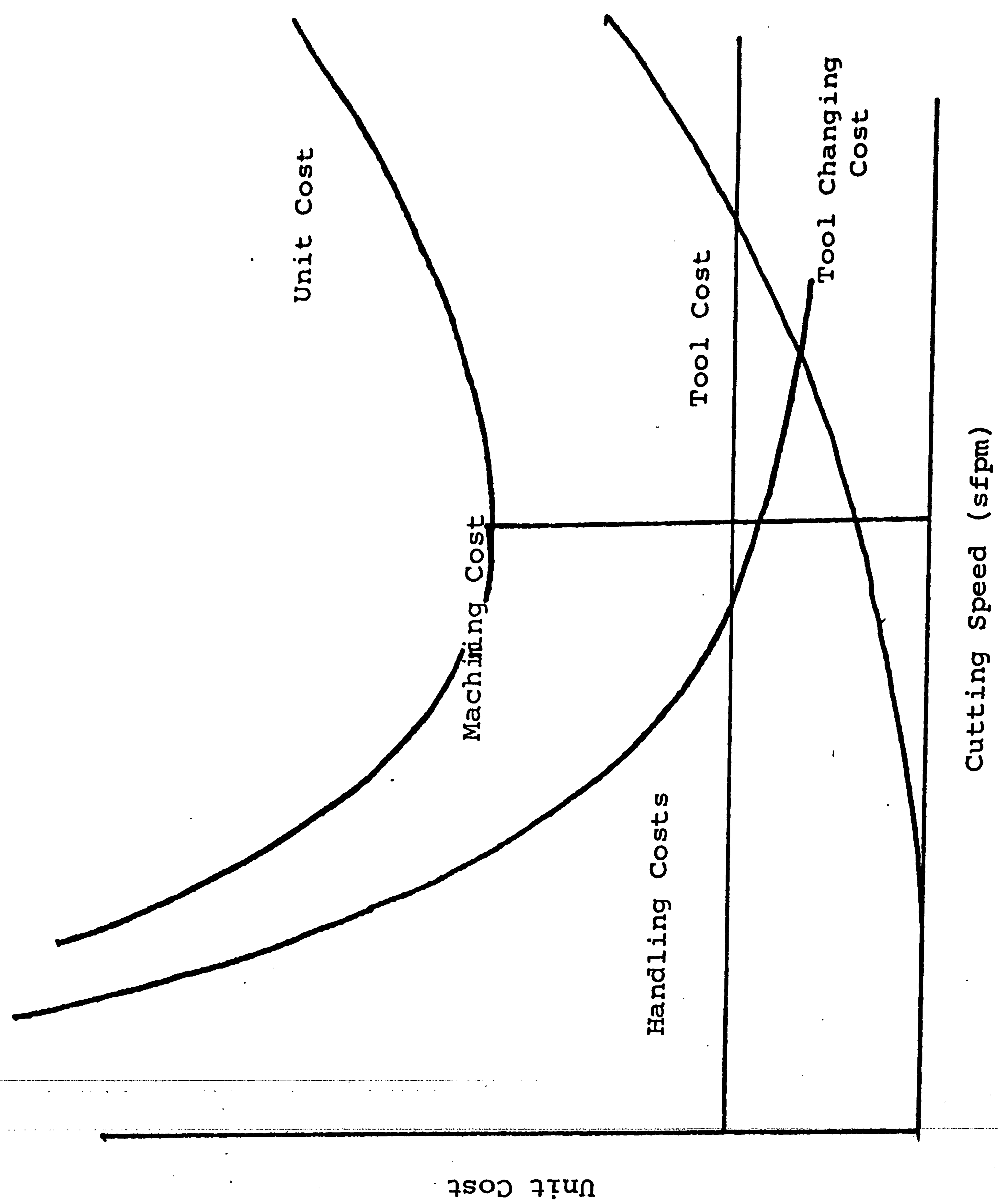


Figure 4

Adapted from:
DeVries, M.F., p.8.

The relationship between speed and tool wear (generally considered to be a power function) is shown in Figure 5. Therefore, tool costs and change time will increase with increasing speed.

If all of the four cost components shown in Figure 4 are added, the result is the total unit cost curve which can be observed to be u-shaped and possessing a minimum cost point. Gilbert and others derived the means for obtaining speed at the minimum cost point. The derivation is shown in Appendix A1 but the important result is that the cutting speed for minimum cost index of performance is:[11]

$$Vmin = \frac{C}{\left(\frac{1}{n} - 1\right)\left(\frac{C_o t_c + C_t}{C_o}\right)^{n}}$$

where

C and n are the constants from the speed only Taylor equation

C_o operating time cost

t_c tool change time

C_t tool cost

It is obtained by "equating the total cost to the sum of the four individual costs, differentiating the cost with respect to speed, and setting the result equal to zero.[12]

---

[11] DeVries, p.7.

[12] DeVries, p. 7.

FLANK WEAR VS CUTTING TIME AT VARIOUS SPEEDS

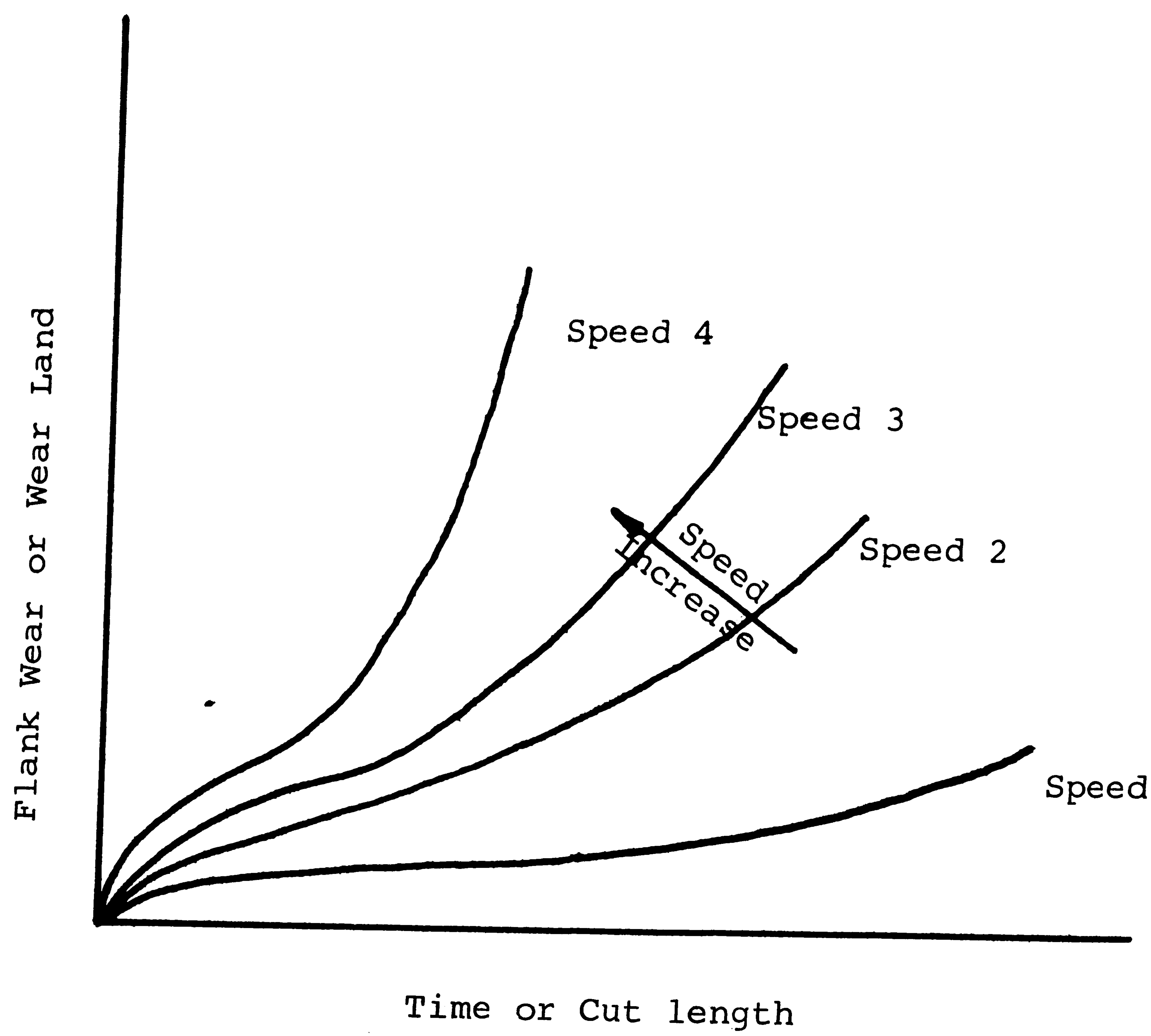


Figure 5

Adapted from :

Vidosic, p. 429.

Gilbert also realized that obtaining minimum cost operation was not always the best objective in all cases. Often it is necessary to run at a greater speed than Vmin to relieve a "bottle neck" situation. For this reason a speed for maximum production rate criteria was evaluated by considering the tool cost to be negligible. Thus the new equation becomes [13]

$$V_{max} = \frac{C}{(\frac{1}{n} - 1)\ t_c^{\,n}}$$

where

V_{max} = speed for maximum production rate.

The minimum cost and maximum production rate indices of performance are the basis of traditional machining economics. Other indices such as maximum profit have been considered but are not as widely used. However, all of these traditional machining economics evaluations are bound, and very possibly rendered useless in some situations, by the necessary assumptions which must be made to use the model.[14]

1) The work material is homogenous. This assumption is necessary in order that Taylor's tool life equation is valid and normal, uniform tool wear occurs. A homogenous material would be one of nearly uniform hardness and micro structure throughout. Some materials, such as the so-called

---

[13] DeVries, p. 9.

[14] DeVries, p. 5.

through-hardening steels, are more homogeneous than others and this assumption is, therefore, reasonable. However, if hardness varies significantly in a workpiece,the result will be varying levels of wear for the same amount of cutting at different points on a workpiece and on different workpieces. Without considering significant material variations, a minimum cost or maximum production rate speed is meaningless on a per piece basis and, most likely, on a per lot basis also.

2) The tool geometry is pre-selected on the basis that it is the best geometry for which tool life data exists. To evaluate traditional machining economics models, the constants n and C must be known. The constants are the result of experimental evaluation and are unique to a particular tool-work combination. Thus, a Taylor curve such as in Figure 2 ~~of Appendix A~~ exists for commonly used work and tool materials. However, tool wear and many other machining factors depend on tool geometry. For example, increasing the side cutting edge angle on a single point tool increases tool life. Therefore,a change to a different tool geometry alters the Taylor constants and require different tool life data. If this data for the appropriate geometry is not available, then an inferior' geometry, for which data is available, would have to be used.

3) The depth of cut and feed are known and constant. This matter has been briefly discussed in relation to the Taylor tool life equation. In that discussion, it was noted that ~~neither depth of cut~~ or feed were included in the unexpanded Taylor model since speed is regarded as a more important

variable. The exclusion of depth and feed in this case may be justifiable from the viewpoint of simplicity. Taylor's equation attempts to give an average tool life time for a uniform tool cutting a uniform workpiece under uniform conditions. Realizing the stochastic nature of metal cutting, the Taylor equation merely offers a "ball park" figure for tool life and the accuracy would probably not improve significantly even if other variables were added.

However, when we consider the optimization of cutting conditions with respect to an index of performance and include only speed in the model, a great deal of improvement may be discarded. The exclusion of depth of cut from an optimization procedure can be justified since depth of cut is fixed by part configuration and often is not even a true "variable". The importance of feed, however, is clearly shown in the equation given earlier for the determination of cutting time.

$$t_m = \frac{L\pi D}{12Vf}$$

To "optimize" cutting conditions by optimizing speed only and by setting feed rate to its limiting value (which can only be estimated according to such factors as tool breakage, surface finish, available horsepower, etc.) could very certainly result in sub-optimal cutting conditions with respect to the index of performance.

The logical question at this point is: What is the purpose of excluding a variable known to be important from the traditional machining economics model? The reasoning will be generally described here but a derivation can be found in Appendix A2. If both speed and feed are to be considered in the model, both variables must be included in the Taylor tool-life equation to show the relationship of the two to tool life. Thus the expanded form of the Taylor equation

$$VT^a f^b = D$$

To determine the optimum values of V and f the partial derivative of the cost equation using this new tool life relationship with respect to V and f is set equal to zero. At this point, a problem occurs because V and f are not equally related to tool life. In fact, the exponential variation of tool life with speed is generally about twice as great as that with feed.[15] For this reason, the two partial derivative equations cannot be satisfied. Therefore, since speed is the more important factor, speed only is optimized with feed set to as large a value as possible with respect to surface finish, etc. This is the only solution possible in the traditional machining economics case, and is certainly sub-optimal.

---

[15] N. Cook, Manufacturing Analysis, p. 161.

4) Sufficient horsepower is available to cut at the economic cutting conditions. This assumption must be made regardless of economic model used.

5) Cutting costs are identical regardless of whether the machine is cutting or not cutting.

Again, an assumption which is essential to any machining economics technique.

6) The Taylor constants n and C are truly constant.

This may not be a logical assumption if significant variations exist in the machining process. A major source of variation, work-piece variation, has been considered but other sources exist which could alter the constants. Tool material inconsistencies, geometry changes, machine and set-up variations and the random nature of the machining process previously discussed are all possible sources.

Traditional machining economics requires that all assumptions be reasonable in order that such an analysis can be used. Certainly, in some cases, the assumptions are feasible. In other cases, all of the assumptions may not be feasible, but the economic importance of the operation is not considerable enough to warrant more sophisticated optimization analysis, and "ball park" average cutting conditions are all that can be justified. In such a case, it is hoped that as the operation proceeds, improved cutting conditions may be found by trial and error.

However, many economically important operations exist which possess significant machining variations or which could benefit from a feed-speed optimization analysis. To apply a traditional machining economics model to such operations would be a mistake, but up until the last several years, little work had been done to find more suitable optimization models. For some time, manufacturing engineers had settled on determining cutting conditions for an economically important part in a sub-optimal, per lot manner, ignoring often substantial variability and the possibility of optimizing cutting conditions on a per piece basis. Today, research is being done to improve this situation through the use of search technique and on-line cutting condition control.

In the following sections previous work will be considered concerning the optimization of cutting conditions using on and also off-line search methods.

Optimization of Cutting Conditions by Use of Search Methods

Adaptive Control

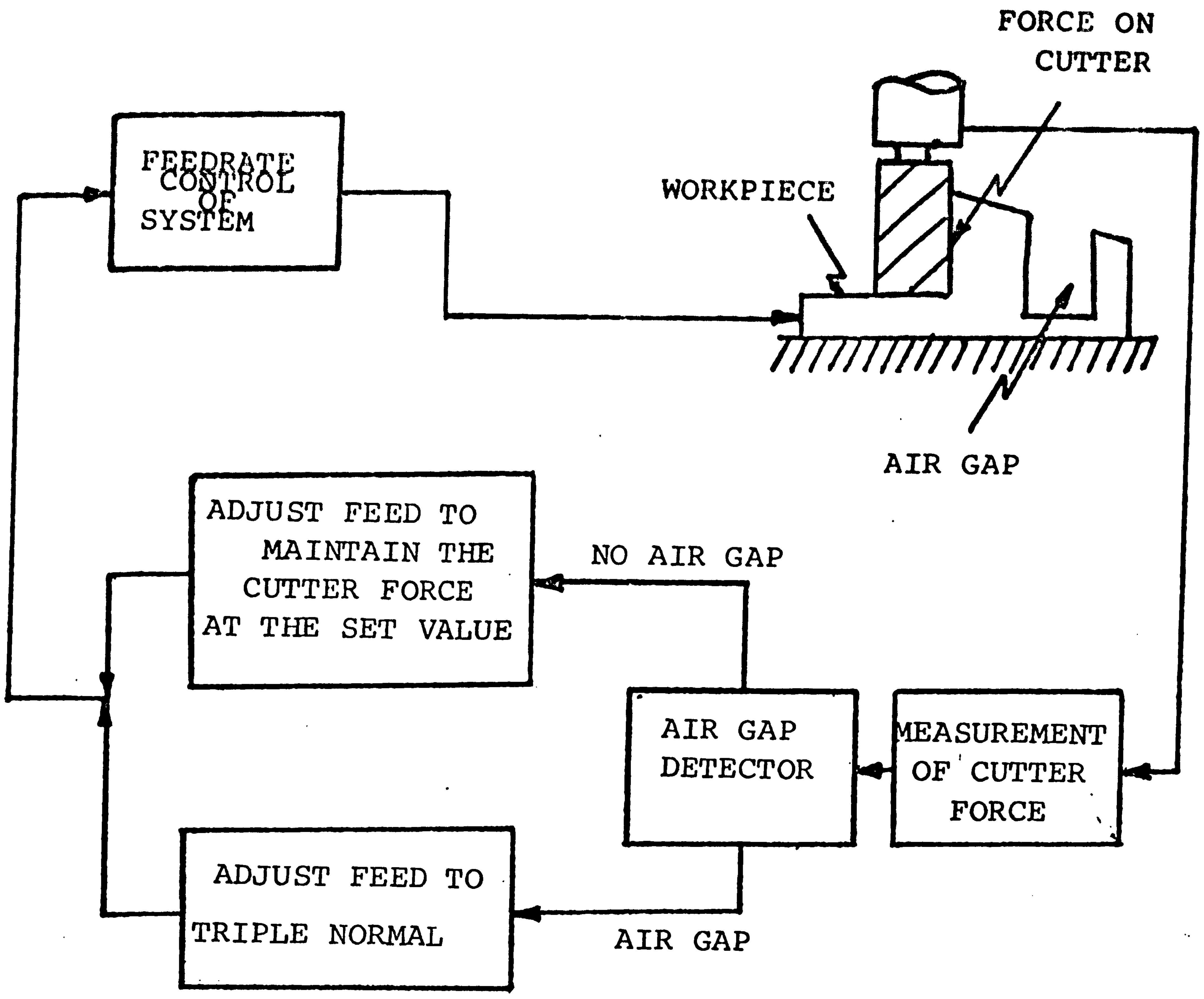
Adaptive control, although not yet widely applied, offers great potential in on-line improvement. Adaptive control when applied to metal machining, involves a control system "in which one or more of the process variables are measured during the cut and some input variable (feed and/or speed) is adjusted to compensate for changes in the measured process variable."[16] The process (or independent) variables used are in some way related to the economics of the machining operation and, therefore, can be regulated according to a search strategy to move the process towards an objective desirable to management. Typical process variables might be force, spindle deflection, torque, etc. All must be quantities which can be reliably detected and measured on-line. It is clear that on-line determination of the instantaneous value of the process variables is essential in A/C in order that continual improvement of the index of performance of a process having random variability occurs. A simple A/C system is shown in Figure 6. Note that the system measures the force on the cutter (process variable) and regulates the feed rate (input variable) to maintain cutter force at a prescribed level. This set level has been previously determined to be economically desirable.

Often the machining situation is not nearly so well defined as in the previous example. In a situation with significant variations, the functional relationships between input and process variables and the index of performance vary with time in an unpredictable way. In this

---

[16] M.P. Groover and R.J. Johnsn, "Alternative Methods for Determining Optimum Machining Conditions", p.2.

A TYPICAL ADAPTIVE CONTROL SYSTEM



Adapted from:
Groover, M.P. and R.J. Johnson, SME Tech. Paper MMR74-203, p. 3.

Figure 6

case, a search strategy is required to determine the shifting optimum index.

Several difficulties exist to this point in the development of adaptive control:

1) In order to accurately determine the economic cutting conditions based on an index of performance, process variables such as tool wear and life and surface finish need to be sensed on-line. The instrumentation to accomplish this is not yet available. A solution to this difficulty has been the sensing of measurable process variables which can be related to the important process variables. The relationships are experimentally determined and most likely induce some error.

2) Instrumentation and controls for A/C are currently too expensive and only a few applications are economically feasible.

3) Realizing the difficulty in measuring important process variables, the selection of an index of performance is an important consideration. A large amount of data must be taken to determine a reasonable and reliable index of performance and the relationships between process variables and the index.

Performance Index Method and Production Optimization Method [17]

The following search oriented techniques used to improve cutting conditions were developed by Inyong Ham and associates at Pennsylvania State University. The Performance Index Method and Production Optimization Method were developed for off-line use and offer a viable means of incorporating machining variability into aspects of traditional machining economics.

"The performance index method (PIM) develops optimum machining conditions through the use of a measurable response to the machining variables or performance index. The particular indices proposed by the method are unit cost, production rate, and profit rate or any combination of these. PIM is a computer based optimization technique which requires test data involving machining time, number of pieces produced per unit time, and the number of tool changes during the time considered.

The method offered suggests that the response surface can be described effectively by cutting speed, feed rate, and the selected performance index. PIM uses a computer program to search the response surface and find the optimum point assuming that initial starting conditions are given. The initial test points can be selected on the basis of machining data available or chosen by the computer program itself based on the assumption that the optimum should generally lie within the upper half of the usable feed range and in the middle two-fourths of the usable speed range but within the horsepower constraint of the machine. The exact endpoints of the "usable" machining parameter ranges are somewhat arbitrarily determined but are realistic estimates of the broad area of search in which the optimum should lie. The computations necessary to find theoptimum value of the performance index are lengthy but easily performed by the high-speed digital computer. The exhaustive search is ended when two sets of test points yield the same result for the performance index.

The PIM program has flexibility built in which allows the user to select the various speed, feed, and horsepower constraints. In addition to turning operations, PIM is adaptable for milling, drilling, and multitool applications. In order to implement the technique, accurate data and in depth analysis of the particular production situation must be obtained. The method is quite feasible technologically and has provided reasonable estimates of the optimum in actual production cases.

Another technique employing computer optimization of machining conditions is the Production Optimization Method (POM). The advantage of this particular method as opposed to PIM is that more accurate optimization is obtained, more useful information is produced, and greater flexibility in the selection of optimum cutting conditions is offered. However, POM requires tool life, cost, and time study data in addition to the necessary PIM information and POM is only applicable to turning operations.

The method itself is based on the analysis of optimum machining conditions through the continuing feedback of tool life information from production tests into the computer program. By this process, general tool life information for a specific operation can be custom-made for accurate application to the particular production situation considered. The testing occurs during normal production. Through the use of multiple regression, the computer program selects a range of optimum machining conditions on the basis of some production objective (e.g. minimum cost, etc.). These conditions consisting of speed and feed combinations for a particular depth of cut are tested one by one until the change in each of the tool life parameters is smaller than some acceptable value. At this point, optimum machining conditions have been obtained for the particular production objective under consideration.

POM appears to provide a successful technique to "taylor make" the tool life equation to a particular turning setup and operation. The concept of optimization has been tested and substantiated by production results. The difficulty in application lies in the problem of attaining accurate input data which describes the production environment."

Self Adaptive Procedure

A third area of investigation in the area of improving cutting conditions using search techniques is the concept of a self adaptive procedure. The procedure described here is the one for which a search technique has been developed in this research. It employs a search strategy which considers the stochastic nature of machining but does not require the elaborate instrumentation of A/C to make constant adjustments to instantaneous machining variations. The self adaptive procedure updates the cutting conditions at periodic intervals to improve the index of performance. Important process variables are not measured on-line but are determined by a series of off-line measurements at different cutting conditions and replications at the same cutting conditions. Replications are required to determine a reasonable estimate of the process variable in light of the variability present in the machining operation. Estimates of process variables at

---

[17] As written by R. Johnson for SME Paper MR74-203, pp. 5-6.

different cutting conditions are used to calculate an estimate of the index of performance at those cutting conditions. The resulting indices serve as input to an optimum seeking search technique. In this way, cutting conditions can be improved and updated at intervals considering the stochastic nature of the machining operation, but not constantly measuring process variables and their instantaneous variations with costly instrumentation.

The important process variables can be related directly to an economic index of performance such as minimum cost per piece. To move the machining operation towards that optimum requires the implementation of a search strategy. The strategy should be capable of evaluating the current index at some feed and speed and determining where to move on the response surface so as to approach a minimum (or maximum). Gradient search technique seems to be particularly applicable to this situation and is evaluated in this research for use in a self-adaptive procedure.

Essentially, a gradient search on the feed-speed response surface can be performed in the following manner:

1) Given a starting condition, place test points around this origin at suitable distances.

2) Determine the value of the important process variables at the test points.

3) Evaluate the index of performance from the important process variables at each of the test points.

4) Determine the feed and speed gradient components.

5) Take a move of predescribed length in the direction dictated by the gradient components.

6) Check the new origin to see if it is close enough to the true optimum to stop the search. If not, continue the search by setting up a new test point pattern.

An example of how such a procedure might adjust feed and speed according to such a strategy is shown in Figure 7.

There are several problem areas associated with the self adaptive approach, some of which are investigated in this research:

1) The variability in the machining process will result in variation of the index of performance for identical cutting conditions. In order to obtain a good and reliable evaluation of the index of performance at a test point set of cutting conditions, possibly several replications at a particular set of conditions may be required. From the resulting values of the index of performance, an average value could provide a reasonable estimate of the index. However, replications require data collection time which is expensive.

SEARCH TO IMPROVE CUTTING CONDITIONS

THROUGH THE MINIMIZATION OF COST/PIECE

CONDITIONS :

- Method of Steepest Descent
- SF Penalty Cost = $.25/def.
- Four point test pattern
- No variability considered

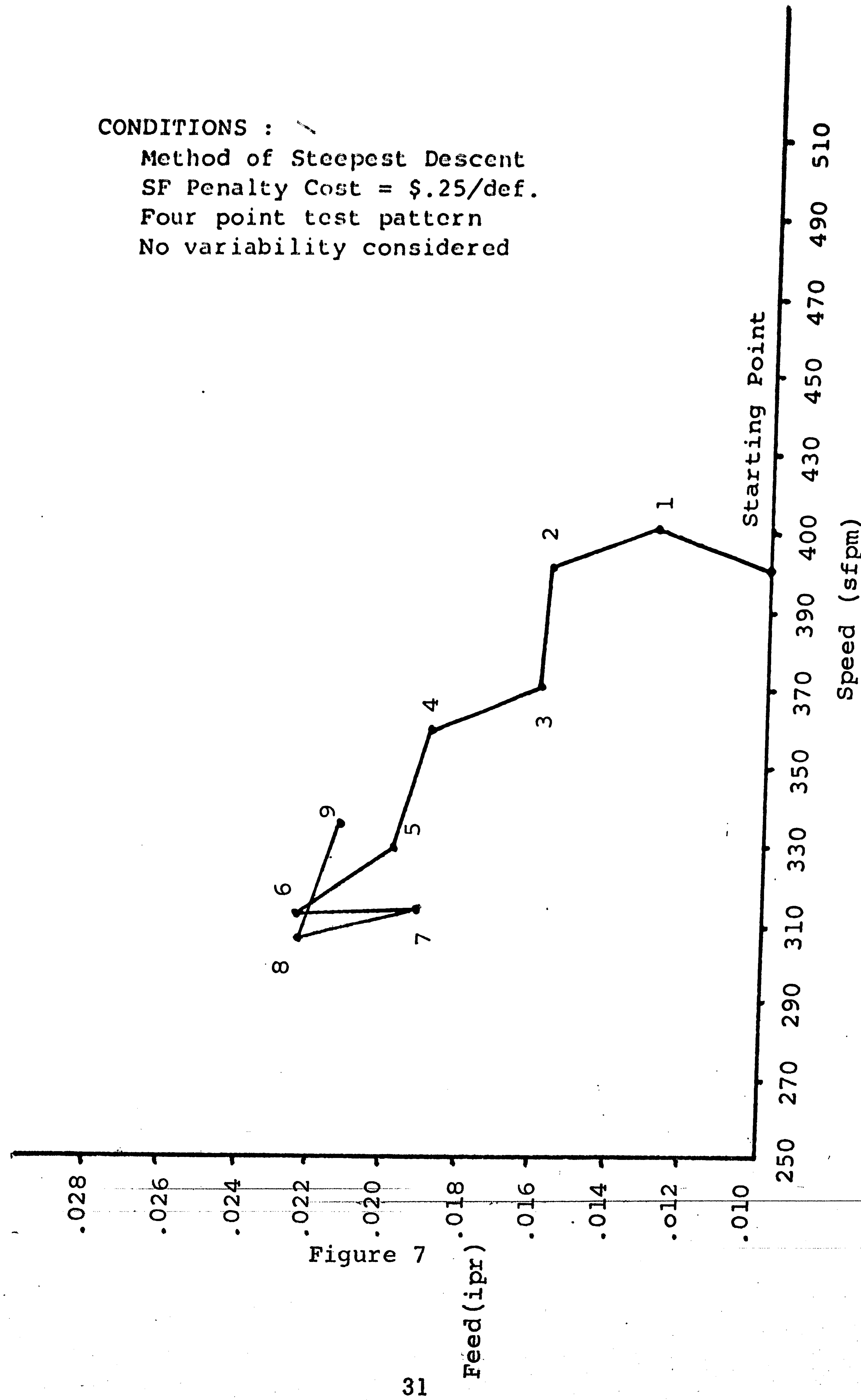


Figure 7

2) The approach requires extensive model building and simulation as a means of testing alternate search methods and search mechanics. The constructed process model would then require verification by actual data taken on the shop floor. Thus, development of such a search-oriented, self adaptive procedure may require expensive computer time in addition to more costly production time.

3) Questions arise relating to the mechanics of the self-adaptive search procedure. What should the starting point be? How large steps should the steps be? What type of search provides adequate results? What is a reasonable index of performance? Many of these problem areas are investigated in this research.

4) Problems also exist in applicability. Certainly this procedure is applicable only to a long run machining operation of economic importance and having substantial variations in machining variables (part geometry, hardness, tool and machine variations, etc.). However, in addition, there is the difficulty arising from the use of a complex search scheme requiring accurate data by a possibly uneducated operator. Economic factors (incentives, etc.) also become important when a human operator becomes part of the system.

The Experiment

Research Plan

The investigation was divided into three distinct phases:

Phase I - Collection of machining data and development of process model.

Phase II - Development of optimum seeking procedure through the technique of computer simulation.

Phase III - Machine Shop Validation and Testing

Phase I resulted in a process model consisting of mathematical relationships for tool wear and surface finish. The process model was particularly useful in giving insight into the amount and significance of machining variability. Phase II involved the development of a computer model based on the results of Phase I. The computer model is capable of simulating the economic consequences of changing cutting conditions. This model was expanded to include an optimum-seeking search method which attempted to improve a given set of cutting conditions on the basis of an index of performance. Phase III applied the search technique to actual machining tests so that the technique could be evaluated and modified as required.

Introduction and Discussion

In order to develop a process model which can be used to report the effect of changing cutting conditions on tool wear, surface roughness, and ultimately, an index of performance to be employed in a self-adaptive optimization procedure, initial data concerning the relationship of speed and feed to measurable dependent variables must be generated. This data was obtained from a turning operation in which tool flank wear, crater wear, and work-surface roughness were measured for a variety of cutting conditions. By developing a model for each of the measured variables, the metal machining operation can be simulated in such a way that the stochastic nature inherent in the metal cutting process can be incorporated into a process model. The results of the simulation study are economic information concerning production rate, machining cost, and defective rate. From these factors, it is possible to derive an index of performance which is the essential measure for an optimum search strategy. An index of performance is necessary to locate the "optimum" cutting conditions for a particular economic objective (minimum cost, maximum production, etc.). Thus, the result of the study is a self-adaptive procedure for metal machining which is not dependent upon the various forms of the Taylor tool life relationships.

Associated with this general experimental procedure of Phase I are several possible sources of error. The following discussion will consider these errors and the steps taken to avoid or minimize them:

1. In most machining process models, the workpiece hardness is considered as an important variable. Hardness variations are common in most metals and can be the cause of over or understated wear conditions, thus injecting error into the model. This type of error was minimized by selecting a through hardening work material, 4340 steel, which offers uniform hardness and reduces the concern over hardness variations. Hardness ranged from 33.5 to 36.3 on the Rockwell C Scale for the specimens machined. A thorough listing of this range can be found in Table I of Appendix B1.

2. Surface rougness can be created not only by feed marks in the normal fashion but also, by long chips curling around the holder and marring the surface. All attempts were made to eliminate the latter type of surface roughness by clearing the chips away

from the workpiece as they were formed. Some scoring of the surface by this means was inevitable, however, at some of the cutting conditions.

3. "Average" flank wear or crater wear is an observer-oriented variable and surely, several observers examining the same tool or a group of tools would record many different measurement values of the same variable. This error was minimized by having one observer only perform the measurements.

4. The assumption of a pattern of wear which includes a break-in period followed by wear at a constant rate with time is used to develop models for flank wear and crater wear (see Figure 8). However, it is clear that for some cutting condition regions, tool wear does not display the relationship shown in Figure 8 but occurs at an accelerated rate suggesting additional mechanisms of wear. This effect of accelerated wear can also be seen to occur near the end of the useful life of the tool as wear increases substantially. These accelerated or abnormal wear regions could not be considered without the development of an extremely

Flank Wear vs. Cutting Time Relationship

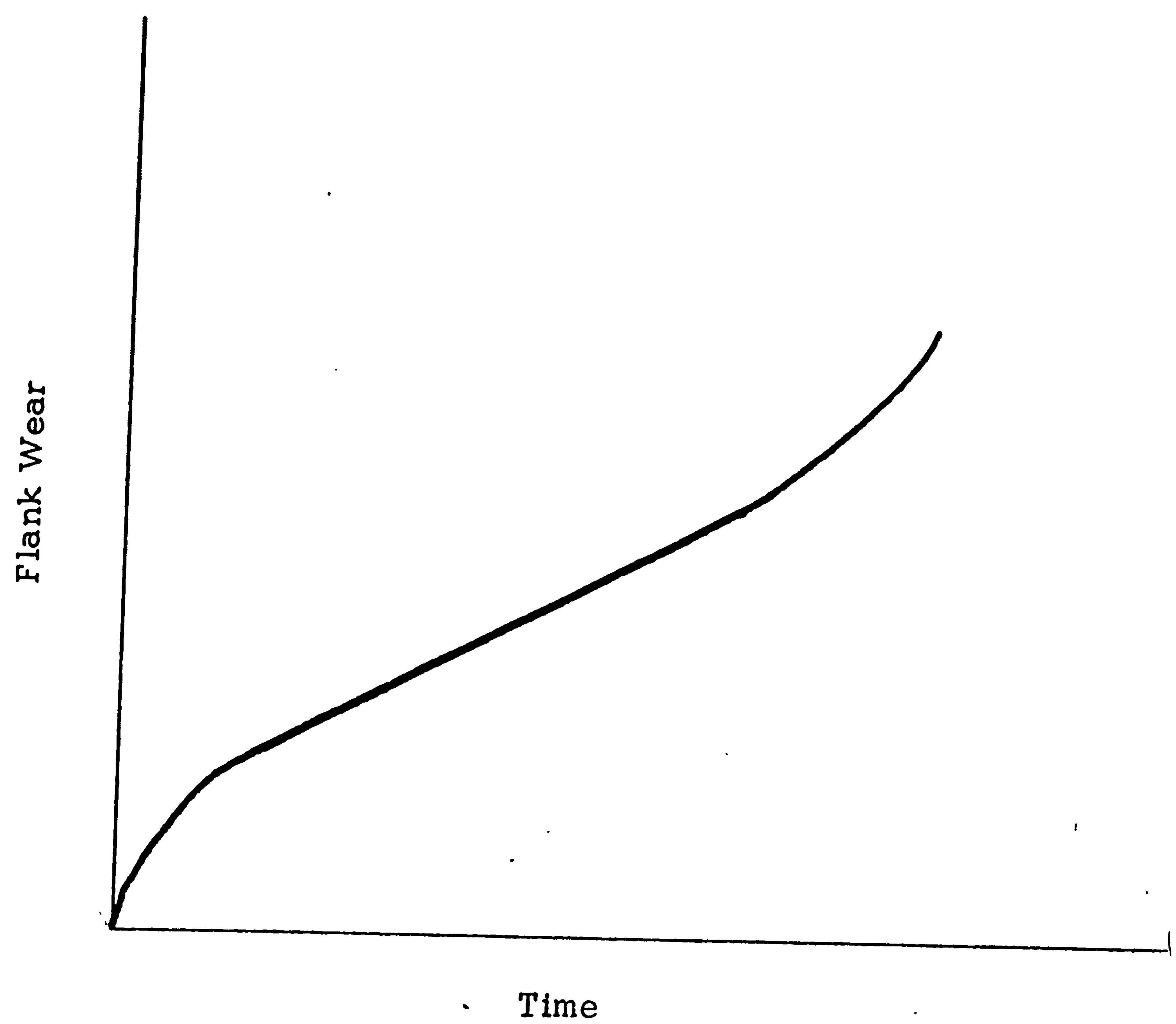


Figure 8

complex and specific tool wear model and for this reason were disregarded. The exclusion of such a factor, however, could result in some error. Attempts to minimize this problem were made by avoiding excessive cutting conditions and stating tool life on a wear criterion well below the level at which accelerated wear rates might occur.

5. The assumption that a pattern of wear which includes a break-in period followed by wear at a constant rate has another potential for introducing error into the model. In Figure 8 it is easy to state the value of the break-in wear by extending the line of constant wear rate back to the wear axis and labelling the intercept as the value of break-in wear. In actual cases, however, one could not expect to measure wear with respect to time and find that all points recorded in the so-called constant wear rate region actually fell on a straight line. A straight line, however, is necessary to determine the break-in wear and error could be introduced into the model by the difficulty in finding the "best" line through the points

recorded. An attempt to minimize this error was made by using a linear least squares analysis of the wear level with respect to time.

Phase I: Process Model Development

Selection of Variables

Work Material. One grade of steel, SAE No. 4340 with hardness of R_C35 on the average, was selected for the research study. This material was selected due to its good hardenability resulting in fairly uniform hardness throughout the work material. Hardness variations would be undesirable since they would have to be considered in the tool wear and surface roughness models. At this time the measuring of instantaneous hardness is technologically infeasible and thus, a material with fairly uniform hardness was chosen to avoid this problem. Work diameters varied from 5.10 inches to 4.00 inches. Pertinent hardness data can be found in Table I of Appendix B1.

Tool.

The tool material used in the experiment was as follows:

WA-6 (Tungsten Carbide) - Walmet Corporation

(Industry designation C-6)

The nominal composition of the Walmet WA-6 Carbide is:

Tungsten Carbide - 82%

Titanium Carbide - 8%

Cobalt - 10%

The hardness of the tool material as listed by the manufacturer is Rockwell A91.2. The tool geometry signature of the carbide square insert was: -5,-5,5,5,15,15,3/64.

Equipment and Instrumentation.

A list of the equipment and instrumentation used in the experiment is given in Appendix B2.

Dependent Variables Measured.

The dependent variables of interest in this study were tool wear, both flank wear and crater wear, and surface roughness.

Flank wear was measured after each cut in the normal manner with the use of the toolmaker's microscope. The variable of interest was actually average flank wear which permits a certain amount of error to enter the measurement as discussed previously. However, in most cases the visual determination of an average flank wear was clear and the error was minimized by one person taking each measurement.

Crater wear was measured after each cut by viewing the tool surface on an optical comparator screen and tracing the crater area on a clear sheet of plastic placed on the screen. The area was then transferred to a piece of paper on which crater wear area measurements could be accurately taken with the use of a planimeter.

Surface roughness was measured after each set of cuts at a particular cutting condition through the use of a surfindicator. The measurements were taken parallel to the axis of the part at the beginning, middle, and end of the cut with three replications at each position. In all nine measurements were recorded per cut (3 positions x 3 replications/position) in order to determine an average roughness over the entire cut.

Design of Experiment

The selection of appropriate cutting conditions is a significant factor in this study and will be considered in detail in this section. Of great importance in the development of a machining process model is the selection of "usable" feed and speed ranges for the carbide tooling used. In this case, "usable" refers not only to application in such a way that the tool is capable of operating without immediate failure but also to usage similar to that which would be found in industry in a wide variety of situations. Thus, "usable" cutting condition ranges ensure realism and usefulness of the model.

It was decided that a model developed on speed ranging from 200 to 600 sfpm and feed from .005 to .030 ipr would be adequate. Depth of cut remained constant since depth is generally specified by part geometry and thus, is not often a variable in the true sense of the word. Depth of cut was established at .075 inches.

The next decision, therefore, was to determine the increments of feed and speed to be tested and then specify the pattern of cutting. A plot of speed vs. feed is shown in Figure 9. The decision was made to use increments of 100 sfpm of speed and .005 ipr of feed to eliminate a tremendous amount of test work which was thought unnecessary. Thus, initially, 5 levels of speed and 6 levels of feed were selected.

The problem was further restricted as is shown in Figure 10 by selecting a pattern of cuts which would eliminate a significant amount of testing time but would provide cutting conditions which would show accurate tool wear and surface finish trends. An examination of Figure 10 reveals a noticeable absence of cutting conditions at speeds greater than 400 sfpm and feeds exceeding .020 ipr. This was done to avoid immediate failures which were likely to occur on the grade of carbide tool selected and was intentionally done from past experience with the

Grid of "Usable" Cutting Conditions

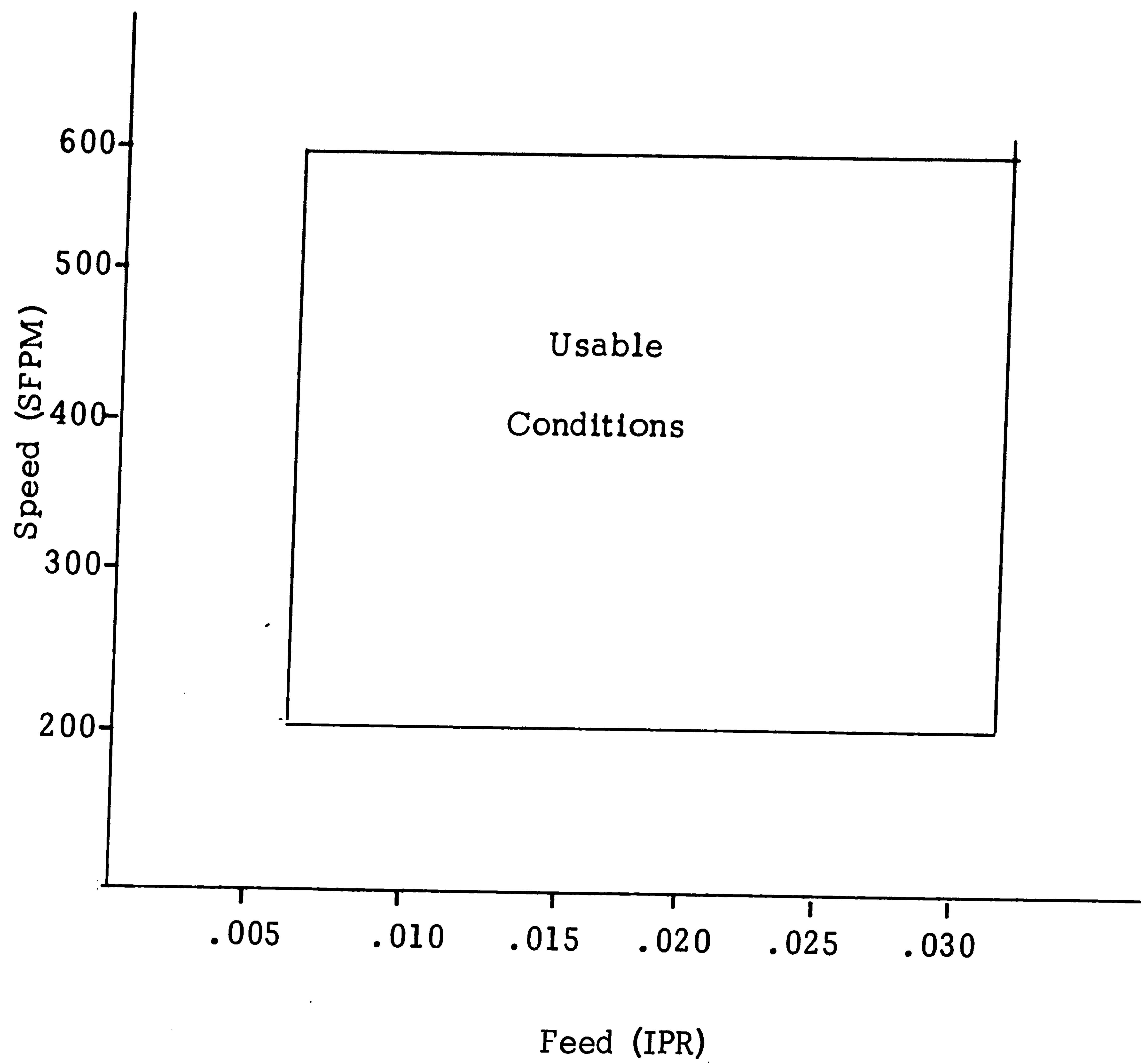


Figure 9

Pattern of Cuts

(Expanded Set)

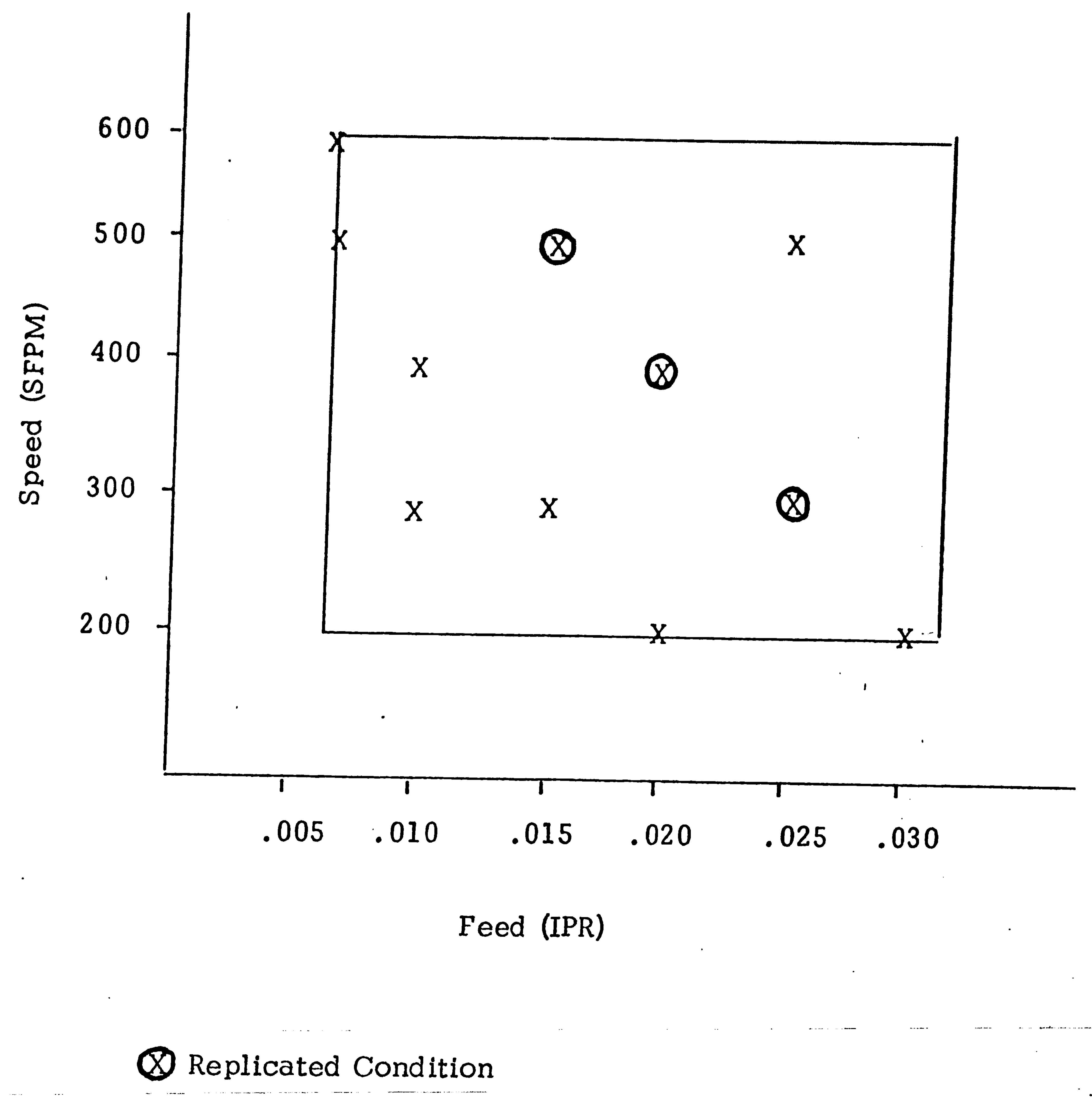


Figure 10

tool grade. Possibly a carbide could have been selected which could perform at all levels of cutting conditions, but the intention of the study was not to test carbides for longevity, but to develop a usable process model without spending excessive amounts of time cutting metal and testing. The pattern of cutting conditions shown was not a rigid structure of testing and plans were made to add other conditions and replicates should the testing and model development reveal that this was necessary.

The 10 cutting conditions which were tested are shown in Figure 11a. The order of cutting was determined by assigning a number (0 through 9) to each cutting condition set and then matching these with a row of random numbers found in the Rand table of random numbers in the Tool Engineers Handbook. After some amount of experimental cutting, it was decided to increase the number of cutting conditions tested to 16 by adding replicates at ($V = 500$, $f = .0147$), ($V = 400$, $f = .0204$), ($V = 300$, $f = .0256$) and additional cuts at ($V = 500$, $f = .025$), ($V = 300$, $f = .0102$), and ($V = 600$, $f = .0102$). This expansion of the experimental set was created to provide replicates and to replace conditions which resulted in immediate failures and thus were rendered useless. The expanded set is shown in Figure 11b.

ORDER OF CUTTING

ORDER NO.	SPEED (SFPM)	FEED (IPR)
1	200	.0300
2	300	.0256
3	600	.0051
4	500	.0147
5	200	.0204
6	300	.0147
7	400	.0102
8	500	.0051
9	400	.0204
10	600	.0147

Figure 11a

EXPANDED ORDER OF CUTTING

ORDER NO.	SPEED (SFPM)	FEED (IPR)
1	200	.0300
2	300	.0256
3	600	.0051
4	500	.0147
5	200	.0204
6	300	.0147
7	400	.0102
8	500	.0051
9	400	.0204
10	600	.0147
11	300	.0102
12	500	.0250
13	500	.0147
14	400	.0204
15	300	.0256
16	600	.0102

Figure 11b

Experimental Procedure

The first step in the testing procedure was to chuck and center the workpiece and to take a "skin" cut to clean up the surface to ensure roundness. To eliminate immediate shock on the tool, the end of the bar held in the tailstock was shaved constantly to provide a suitable starting place for the tool.

The procedure followed for making an experimental cut was to first measure the workpiece diameter. The specified surface speed was set with Varidyne and checked by a tachometer. Feeds and depths were set on the lathe, a fresh tool set in the holder, and the feed was then engaged. Cuts were made for one-half or one minute durations depending on the amount of wear expected on the tool. At the heavier cutting conditions (high speed, and high feed) tool wear was quite rapid and thus, one-half minute cutting increments provided a more meaningful measure of the wear changes. One minute increments were adequate for the lighter cutting conditions.

After the first increment, and each successive increment, the tool was removed and allowed to cool for several minutes to permit handling. When cool, the tool was placed in a vise and examined under the toolmaker's microscpe to measure flank wear. An average value was recorded in all cases but comments were noted if an unusual wear condition developed (e.g. a large wear spike, tool crack, catastrophic or temperature failure, etc.). Keeping the tool in the vise, the tool surface was then viewed on the optical comparator screen to measure crater wear. On the screen was placed a plastic sheet, on which the crater area was traced with a wax pencil. This area was then retraced onto onion skin paper marked accordingly (Speed, feed and time).

Following the crater wear measurement, the tool was reinserted into the holder, making certain that the same edge would be used for cutting. The end of the last cut was marked with a wax pencil to assure proper surface roughness measurement when all cuts at a particular condition were completed. This procedure of cutting for a time increment, then examining the tool for wear continued until one of three conditions occurred:

1. The tool edge broke or cracked
2. Flank wear exceeded .040"
3. A gradually increasing level of flank wear was obtained over ten minutes of cutting.

If any of the stopping conditions occurred, the surface roughness for all of the cuts at a particular condition on a tool edge was measured using the surfindicator. Surface roughness measurements were taken at the start, middle, and end of the cut with three replicates at each position. It was felt that such extensive measurements could offer a good average of surface roughness over the entire cut. When surface roughness was recorded for the entire set of cuts at a particular cutting condition, a fresh tool edge was placed in the holder and the preceding sequence was repeated for the next cutting condition.

When all experimental cutting was completed, the crater wear areas found on the onion skin paper were converted into square inches by the use of a planimeter and recorded on the data sheets. A sample data sheet is shown in Figure 12. Summaries of flank wear, crater wear and surface roughness are found in Tables I to III of Appendix B3.

Methods for Data Analysis

The results of the experimental machining phase of the research study provided the information necessary to produce a process model based on tool wear and surface finish. The actual data used involved measurements of flank wear, crater wear, and surface finish at a cutting time for a particular speed and feed rate. This data is shown in Tables II through III of Appendix B3.

DATA SHEET

DATE ____________

MATERIAL ____________

TOOL ____________

WORK DIAM. ____________ IN.

TEST NO. ____________

TRAIL NO. ____________

CUTTING CONDITIONS

SPEED ____________ SFPM

FEED ____________ IPR

DEPTH ____________ IN.

RESULTS

		TIME (MIN)							
DEP. VAR.		1.0	2.0	3.0	4.0	5.0	6.0	7.0	
FLANK WEAR	AVG.								
	MAX.								
CRATER WEAR									
SURFACE FIN.	START								
	MID.								
	END								

REMARKS:

Figure 12

By developing models for tool wear and surface finish, the economic variables, such as production rate, cost per piece, and defective rate can be determined by Monte Carlo simulation techniques. This was accomplished by specifying tool life limits on the basis of flank wear, where .040 inches of flank wear denotes the tool life. In addition, tool life was constrained by product variable requirements, that is, those design specifications which result in desirable quality of the finished product. This particular research considered surface finish as a product variable constraint which, when exceeded, could denote the end of the useful life of the tool or result in the levying of a penalty cost for a defective part.

The completion of a Monte Carlo machining simulation provided the means needed to test the effects of speed and feed changes on an economics-based index of performance used to optimize the process. Thus, different optimization strategies could be tested on a meaningful basis through the development of a machining simulation incorporating the random variations so common to metal cutting.

A Model of the Machining Process

The quantities of economic interest produced by the simulation are only valid if the mathematical process model representing the metal cutting situation is accurate and dependable. The process model considered in this study was comprised of sub-models of flank wear, crater wear, and surface finish. The sub-models were directly derived from experimental data obtained in the laboratory.

Tool Wear Sub-Models

The tool wear sub-models, comprised initially of flank wear and crater wear, were developed according to the following list of specifications:

1. The shape of the tool wear vs. time relationship is represented by the curve suggested by J. Taylor of Figure 13. This plot was considered representative, for the most part, of the wear vs. time curves generated experimentally for the range of cutting conditions considered. Thus, the wear sub-models assume that a common wear mode exists at the relatively "moderate" conditions tested. The characteristics of the wear relationship include a break-in period at the beginning of a cut with a fresh tool. The break-in is considered to be a period of rapid, accelerated wear, which is followed by a uniform wear rate approximated by a linear function.
2. Although the tool wear process is related to cutting conditions and work material, it possesses a stochastic character which

FLANK WEAR VS CUTTING TIME RELATIONSHIP

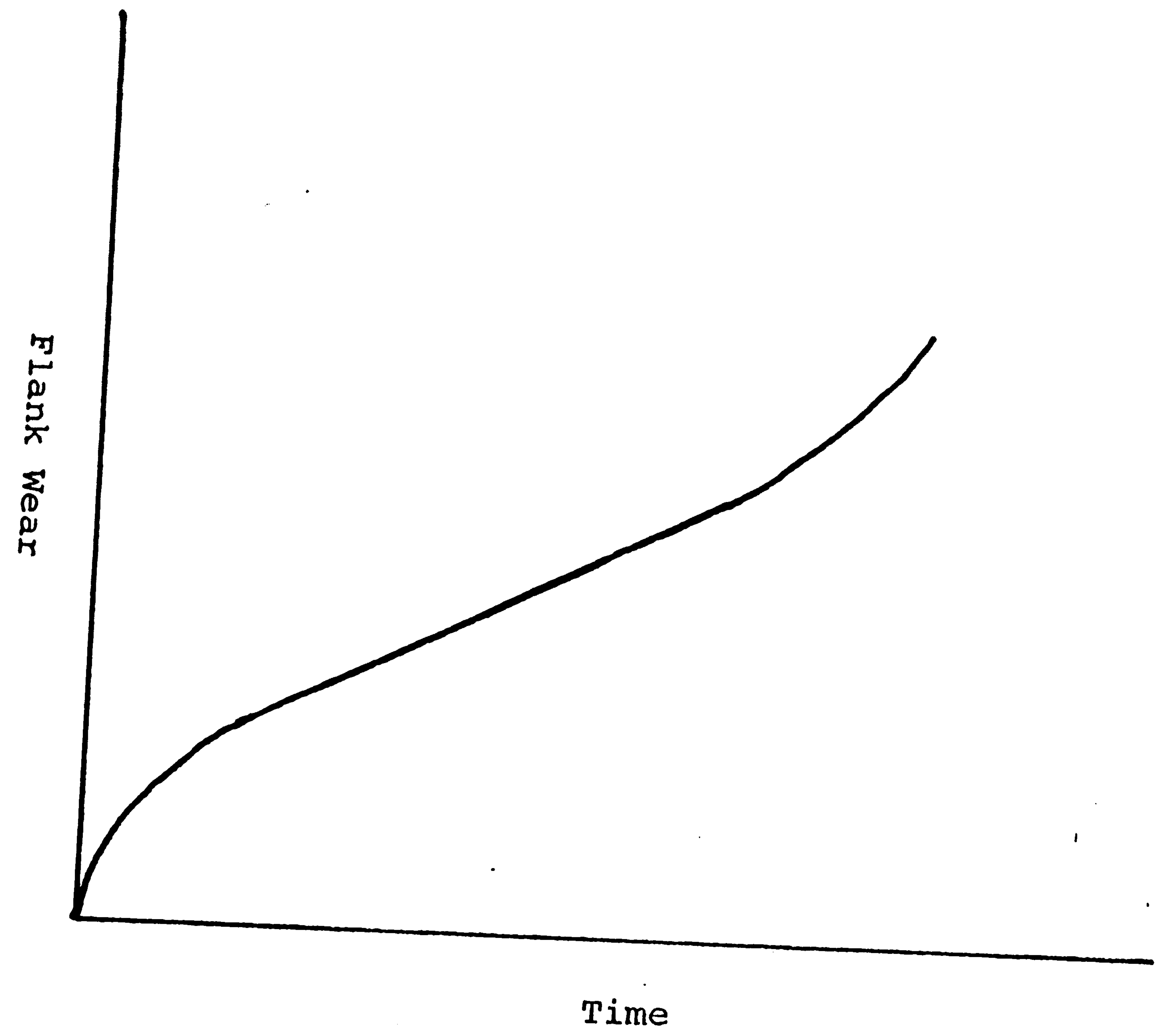


Figure 13

can be simulated by the addition of a random term generated by Monte Carlo techniques.

3. As was previously stated the machining process model contains a tool wear sub-model and a surface finish sub-model. Since surface finish is generated by the cutting tool being fed across the work surface, it was assumed that the condition of the tool has an effect on the surface roughness of the part. Thus, to evaluate the tool status more completely, tool wear was measured at two locations on the tool: on the flank and on the surface of the insert. It was hypothesized that both measurements might have causal effects on surface finish.

The above specifications were satisfied by a mathematical model for wear, combining the break-in and uniform wear rate concepts. For flank wear, the break-in period can be described as follows:

$$FW_o = Q_1 (V, f, e_1) \tag{1}$$

where FW_o = flank wear axis intercept value obtained by projecting the flank wear vs. time curve back to time zero. Units are in inches of flank wear.

Q_1 = function of speed V, feed f, and a random variable term, e_1, which provides the function with its stochastic characteristic.

The uniform flank wear rate is determined by :

$$FWR = Q_2 \ (V, f, e_2) \tag{2}$$

where FWR = flank wear rate in units of inches of flank wear/min.

Q_2 = functional relationship of cutting conditions and a random variate, e_2.

Combining equations (1) and (2), the average flank wear at time t can be simulated by the following composite equation:

$$FW = FW_o + FWR \times t \tag{3}$$

It must be realized that the term, FW_o, represents a fictitious quantity and has no real, physical counterpart. The break-in variable is used to merely simplify calculation and provide a reasonable approximation of the initial wear period.

In an actual cutting situation where many pieces or cuts of time t may be performed with the same tool, equation (3) becomes:

$$FW = FW_o + \sum_{i=1}^{n} FWR_i \times t_i \tag{4}$$

Equation (4) considers the stochastic aspect of metal cutting described earlier by allowing for different wear rates and cutting times for the same tool. The subscript i is employed to identify the workpiece or the cut of time length t. An identical model was considered for crater wear and will not be considered separately for this reason.

Surface Finish Sub-Model

As mentioned earlier, it was assumed that surface finish was related in some way to flank wear and crater wear in addition to cutting conditions. Therefore, the sub-model used to simulate the generation of a surface finish :

$$SF = Q_5 \ (V, f, FW, CW, e_5) \tag{5}$$

where SF = surface roughness measured in average microinches

Q_5 = function of cutting conditions, flank wear, and crater wear plus a random term, e_5.

Method of Model Development

For all sub-models described above, a least squares computer package was used to statistically evaluate the equations for the dependent variables. In addition, from past experience with such models, it was decided to use an equation in which the independent variables were related to the dependent variables of interest by some power evaluated by least squares regression techniques. This type of model is common in metal cutting and can be linearized for easy manipulation.

The linearization is accomplished by a natural log transformation of the following equation: (Flank wear Break-in is used as an example)

$$FW_o = A\,V^n\ f^m \tag{6}$$

$$\ln FW_o = \exp\ (A) + B \ln V + C \ln f \tag{7}$$

where A, B, and C are constants determined by least squares analysis of the linearized form.

The process model is therefore, composed of five smaller sub-models:

1. Flank Wear Break-in, FW_o
2. Flank Wear Rate, FWR
3. Crater Wear Break-in, CWR
4. Crater Wear Rate, CWR
5. Surface Finish

From these five smaller sub-models, the three major sub-models of the process model were developed, as mentioned previously:

1. Flank Wear, FW
2. Crater Wear, CW
3. Surface Finish, SF

Although flank wear Break-in is used as an example, all other smaller models (i.e. FWR, CW_o, CWR, and SF) were developed by precisely the same procedure. The first operation to be performed on the data set was a plot of the dependent variables, flank wear, crater wear, and surface finish, vs. time for all 14 cutting conditions tested. (Note: two cutting conditions created immediate tool failures and were, therefore, dropped from consideration, see Figures 9 to 11). The plots were intended to determine whether or not the curve relationship proposed for tool wear (Figure 13) was prevalent and to see how one could expect surface finish to change with time and wear. For the wear curves, the hypothesis of a relationship approximated by a break-in followed by a uniform wear rate was found to be justified in almost every case. In most cutting samples, surface finish became poorer with increasing time, but not markedly worse.

The analysis proceeded by taking the average wear measurements for each of the 14 cutting conditions and separating the average wear into break-in and wear rate components. This was accomplished by performing a least squares regression of order one on each of the cutting conditions. The coefficient of the independent variable, time, thus became the slope of the period of uniform wear line or the wear rate. The constant of the linear regression was interpreted as the break-in wear, since it physically represents the intercept of the wear rate line on the wear axis at time zero. For nearly all cutting conditions, this type of analysis provided very good fits characterized by small standard errors of estimate, high correlation coefficients (.90 or greater), and small and random residuals. The results of the analysis at this stage, therefore, were the break-in and rate components for both flank wear and crater wear. This stage could be entirely eliminated from the surface finish analysis since the average surface finish does not have a break-in or rate component.

The next step was to create the five small models for FW_o, FWR, CW_o, CWR, and surface finish, SF. The FW_o model will be considered here. The equation was derived by multiple least squares regression of the linearized form of flank wear break-in:

$$\ln FW_o = \exp(A) + B \ln V + C \ln f \qquad (8)$$

The least squares computer program converted the flank wear break-in values determined in the previous stage of analysis, the speed, and feed rate to natural log form, thus, permitting a linear regression. The results of the regression were three constants, A, B, and C, plus a statistical analysis of the regression. This stage was performed for flank wear rate, crater wear break-in, crater wear rate, and surface finish. The surface finish model necessarily had to be developed after the wear models, since surface finish was hypothesized to be related to tool wear.

The final step in model development was to refine the equation somewhat by regressing the actual value of the dependent variable vs. the value predicted by the equation from the previous stage. This step served to tune the model by making minor corrections. However, in the final model consideration, this step was dropped since the corrections did not improve the model enough to warrant the addition of this further complication to an already complex equation.

Results of Phase I

The sub-models developed for flank wear and crater wear are presented in Table I and II of Appendix B4 respectively. These models are each the composite form comprised of a break-in period and a uniform wear condition. The final surface roughness sub-model can be found in Table III of Appendix B4.

Flank Wear

The statistical analysis of the flank wear sub-model considers the two components of flank wear, FW_o and FWR, to accurately provide for the stochastic nature of the machining process. Thus, in the development of the flank wear at any time t, the natural log of flank wear break-in is calculated and a random variate added which is produced from a normal distribution with mean zero and standard deviation equal to the standard error of estimate, S_e, of the log transformed data. Then, to the antilog of this was added the antilog of the wear rate plus a generated wear rate random variate multiplied by the cutting time on the tool considered.

$$FW = e^{(FW'_o + e_1)} + \sum e^{(FWR' + e_2)} \times t$$

where e_1 = a random variate which can be determined as above
FW'_o = ln (FW_o)
e_2 = a random variate determined as e_1 except for FWR
FWR' = ln (FWR)

To consider this type of analysis, the residuals from both the flank wear break-in and flank wear rate regressions must be shown to be normally distributed with mean zero. This was assumed to be true from an analysis of the residuals, thus, permitting the selection of random variates from a normal distribution with mean zero and standard deviation equal to the standard error of estimate of the regression equation under consideration. The sub-model for flank wear was developed for simulation by Monte Carlo.

For flank wear break-in, the value of S_e was found to be .394126 for the log transformed data with multiple correlation of .9014. For flank wear rate, the value of S_e was calculated from the log transformed data as .442034 with a multiple correlation of .8857.

Crater Wear

The same analysis described for flank wear was applied to the crater wear data with the following results:

	S_e	R
CW_o	.211677	.9073
CWR	.443038	.8172

Surface Finish

Initially, the surface finish model was developed containing both flank wear and crater wear as independent variables in addition to feed and speed. However, a stepwise regression clearly showed that crater wear had little effect on the value of surface finish and was therefore, dropped from consideration in the finish sub-model. The sub-model form that remained was:

$$SF = D\, V^b\, f^c\, FW^d$$

The calculated constants D, b, c, and d are shown in Table III of Appendix B4. The standard error of estimate was used in an identical manner explained previously and was found to equal .31928. The multiple correlation was .89322.

Comments on the Analysis of Data

1. Use of Multiple Correlation and Standard Error of Estimate - In all of the regression computations the correlation coefficients were relatively close to 1. It must, however, be kept in mind that the correlation coefficients were computed using the log transformed data. This had the obvious effect of reducing the range of values of the variable and accounts in part for the high value of the correlation coefficient calculated. This complication is also true of the standard error of estimate.

   In addition, a comment should be made in defense of the use of the log transformed standard error of estimate to generate a random variate for Monte Carlo simulation. Using flank wear break-in as an example, the flank wear estimate is obtained by adding a normal random variate from a normal distribution of mean zero and standard deviation equal to the standard error of estimate to the log FW. Taking on the antilog of this sum produces a simulated value of flank wear break-in. This procedure causes the deviations in the positive direction to tend to be greater than the deviations in the negative direction. This was observed to be true in the actual cutting data.

2. In the flank wear sub-model, two cutting conditions were dropped from consideration and both occurred at a speed of 500 sfpm and a feed rate of .0147 ipr. The data was discarded due to tremendous improvement seen in the model when this data was removed. The discarding of these data points can be justified only by considering the nature of the condition. These data were obtained from cutting conditions which were more severe than the other more moderate cuts. This suggests that a different mechanism of wear may have been operating at the more severe conditions. It is well know that when heavy wear occurs on the tool, the result is a break from the uniform wear rate trend to a period of accelerated wear before failure. This period is not considered in this study for two reasons: 1) The relationship is too complex and not well defined; and 2) When this type of wear occurs, the tool is almost certainly beyond its useful life. However,

if such a wear mode exists, it is likely that this condition may have an influence on heavier cutting conditions in a more rapid and significant manner than on moderate cutting conditions. (Note, that the terms heavy and moderate cutting conditions are with respect to the grade and type of tool used). Thus, this accelerated wear mode may have created a different wear pattern than the one assumed in this study in Figure 8. for the condition of speed equal to 500 sfpm and a feed of .0147 ipr.

Phase II Development of an Optimum-Seeking Procedure

Use of Process Models in a Computer Simulation of a Turning Operation

Once the process model had been determined, a computer simulation of the turning operation could be developed. The purpose of such a simulation was to determine the economic consequences of changes in cutting conditions. Thus, simulation would be an effective tool to test various optimization strategies on a meaningful economic basis without actual shop metal cutting. As previously labelled, this simulation is a Monte Carlo simulation, since random variates selected from experimentally defined distributions are generated and used to simulate the variability in the machining process.

The program itself is written in FORTRAN for the CDC 6400 system and contains two parts: 1) Calculation of the process model. Fortran IV was more than adequate for this simulation. Monte Carlo simulations such as this one do not require the filing structure advantages accessible to the specialized simulation languages such as GASP II and Simscript. 2) Computation of Economic Data. The two sections will now be considered.

Calculation of the Process Model

The basic results of this section of the program are the flank wear, crater wear, and surface finish for a particular length of cut at a set of cutting conditions. It is assumed that the length of cut specified represents a workpiece produced. Thus, this simple turning is to be performed repetitively until the tool either exceeds a specified flank wear level or can no longer produce pieces within the surface finish specification. Should the surface finish not be critical to the operation, such as in roughing, the surface finish constraint can be in effect eliminated and tool life will rely on the flank wear criterion alone. Another similar option available allows the surface finish specification to be exceeded and the tool life criterion again is the specified flank wear level. However, for those parts which are not within specifications, each is designated as a defective part and data thus becomes available to make an economic judgement concerning the expense added by trying to increase the production rate by running the tool as long as possible, until both wear and surface finish criterions are exceeded.

The necessary data for the program consists of the various constants and standard errors of estimates for the process sub-models. In addition, the workpiece length, work diameter, cost/piece, labor, rate, tool cost, tool and workpiece change times, cutting conditions, number of tools to be considered at one cutting condition, surface finish specification, and the cost of exceeding the surface finish specification must be read into the program as input.

Once the data has entered the program, the flank wear, crater wear, and surface finish are calculated as described previously including a random variate drawn from the appropriate distribution. These calculations are made for each piece until the surface finish specification and the flank wear criterion are both exceeded. Total cutting time and the number of defective parts produced are accumulated for each tool considered at a particular cutting condition.

Computation of Economic Data

The economic information provided by the simulation involves production rate, cost per piece, profit per piece, and tool life. All of these quantities are accumulated over the number of tools to be tested at a particular set of cutting conditions, and an average value calculated.

Cost per piece is calculated as follows: CPC

$$\text{Cost/pc} = RL \times TDW + (RL \times (TC + TDT)/NPC) + SFC/NPC$$

where RL = Labor rate

TDW=Work change time

TC = Total Cutting time with a particular tool

TDT = Tool change time

NPC = Number of pieces machined with a particular tool

SFC = Total cost for producing parts above surface finish specs

Total Production Time per piece : TPC

TPC = TDW + (TC + TDT)/NPC

Prodution Rate : PR

PR = 1/TPC

Profit per minute per piece: PROF

PROF = (PRICE-CPC)/TPC

These calculations are repeated for each tool tested at a particular cutting condition as mentioned, and the average quantities determined. The averages are very meaningful since the individual tool results may incorporate random variables which are extreme but nevertheless realistic to the wide variations which occur in machining. The average offers a reliable estimate of each of the important economic quantities which can be considered to be potential indices of performance in the search scheme to be described.

Development of an Optimum-Seeking Procedure

Once the computer simulation of the turning process was tested satisfactorily, the computer model was expanded to include an optimum-seeking search procedure. The expanded simulation model used the economic results of the initial process simulation to determine the value of the index of performance selected at the test cutting conditions surrounding the starting point of the search. A wide variety of search procedures, capable of improving cutting conditions by directing the simulation towards a desirable condition of the index of performance could be used in the optimum-seeking model. In considering the selection of a search strategy and the mechanics associated with such a procedure, it was found that the following areas had to be investigated concerning the development of a self adaptive procedure to improve cutting conditions.

1. Type of Simulation Search

Essentially, there are two types of searches, gradient and non-gradient. Gradient searches include the method of steepest ascent (or descent in a minimization objective) and variations of this method. Non-gradient techniques include trial and error or improvement type strategies. If the variability in the index of performance is not too great, gradient strategies offer maximum efficiency of movement. Thus as a start, gradient-type searches were investigated and tested using the computer model. For the machining conditions search, it was found that gradient techniques were highly satisfactory.

Two types of gradient searches were tested. First, the method of steepest descent, was examined. Such a method uses the evaluation of an index of performance at each test point surrounding the origin point to determine a vector quantity of the trend (gradient) of each independent variable. The sizes of the gradient components affect the length of the step while the signs reflect the direction of movement.

Secondly, a gradient search type used by Box and Draper in "evolutionary operations" was considered. In this technique a step is taken to one of the test points surrounding the origin. Thus, only the signs of the gradient components have any significance. A sample of both the method of steepest descent and the variation technique are given in Figure 14 .

COMPARISON OF MOVEMENT UNDER IDENTICAL CONDITIONS:

METHOD OF STEEPEST DESCENT AND VARIATION GRADIENT METHOD

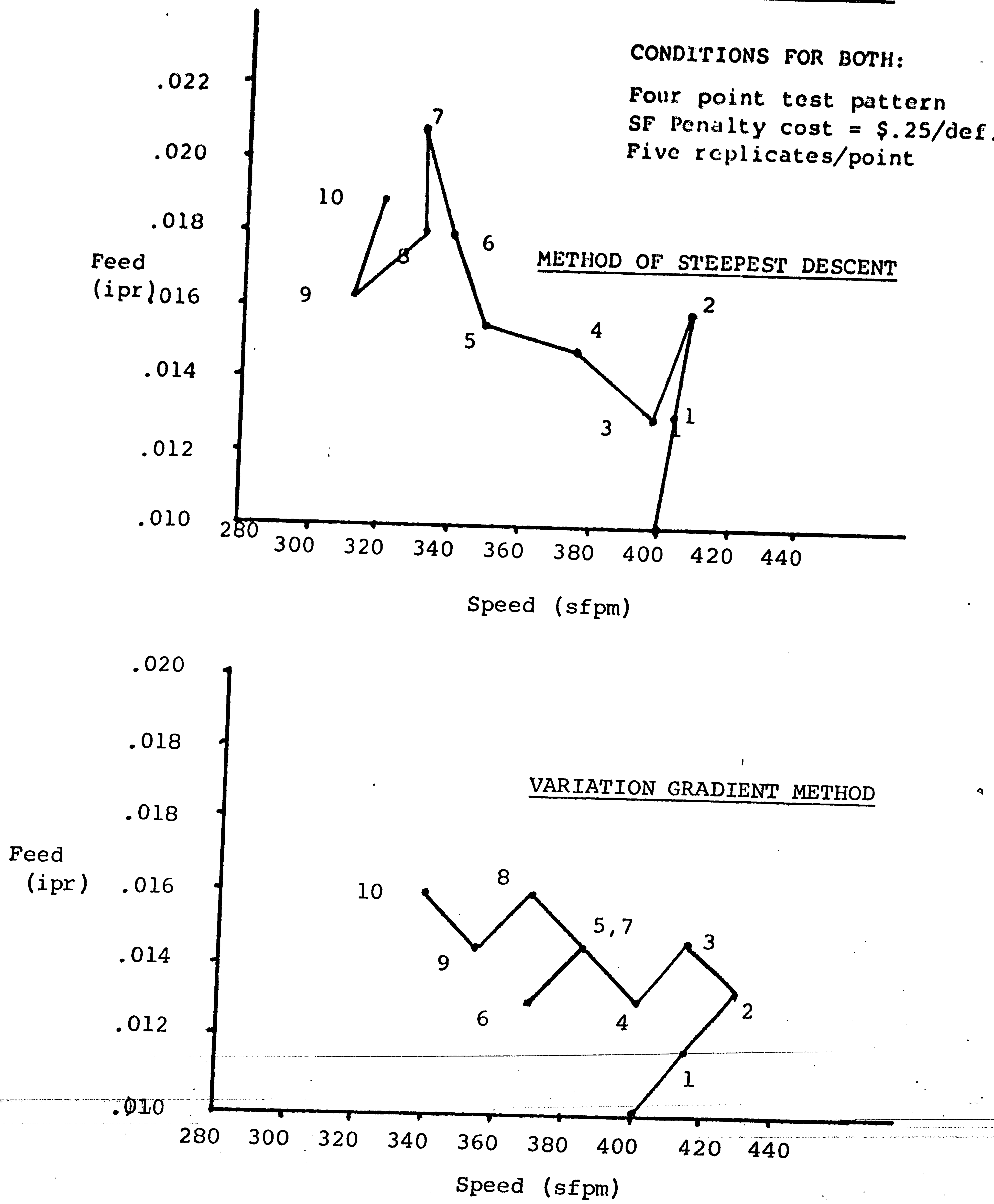


Figure 14

2. Index of Performance

The selection of an index of performance has a great effect on the results obtained by the search strategy. The index chosen should reflect the feeling of management concerning the particular operation for which a search for improved cutting conditions has been considered. A minimum cost per piece or per cubic inch of metal removed is desirable for a long-running operation capable of reliably producing the quantity of product required. Since such a self-adaptive search as the one described in this research would only be applied to a long term, economically significant operation, minimum cost per piece (or per cubic inch) was selected for study in this research. Other justifications for the selection were that the minimization of cost is a well-known and well-studied index in traditional machining economics and such a comparison between the deterministic solution of traditional machining economics and the probabilistic solution presented in this study could be enlightening and informative. It should be noted, however, that the computer simulation model could be easily adapted to perform a search on the basis of maximum production or profit rate criteria.

Several important considerations concerning a minimum cost model must be discussed before an experimental model can be tested.

1. Having seen the shortcoming of the Taylor tool life model, how should tool life be defined in light of the presence of machining variability?

   As described earlier, substantial variability was found to exist in the machining operation examined, thereby, justifying the use of atleast two replications at each cutting condition test point in the test pattern. Thus, it was feasible to consider a flank wear criterion-based tool life and to obtain knowledge of the tool life which could be expected at a particular set of cutting conditions by averaging the replicate wear values.

2. In an evaluation of metal cutting costs in traditional machining economic analysis, it was seen that cost is based on four components: 1) Machining Cost; 2) Tool Cost; 3) Tool Change Cost; 4) Work Change Cost. However, in an optimization situation which

contains variability, it is reasonable to assume and to expect defective parts. But one would not want to "optimize" cutting conditions with respect to the four components mentioned and produce a great deal of defective parts. For this reason, a cost for producing a defective due to exceeding a surface finish specification was added to the minimum cost model. It was felt that such a constraint would permit the application of the self-adaptive procedure to both roughing and finishing operations. For roughing with no surface finish requirements, the surface finish penalty cost could be set at zero and the search for cutting condition constrained only by horsepower or chatter considerations. For finishing, a penalty cost related to rework or scrap cost could be assigned for exceeding specifications. A desirable feature of such a scheme is that a high scrap cost assigned to a part with many operations performed previously or a piece of expensive material, would necessarily result in cutting conditions which would produce very few defectives. On the other hand, a relatively low cost, high production item would be assigned a low penalty cost permitting high removal rates and therefore, high production rates but with a more substantial number of defectives.

3. Tool Life Criterion

In this study tool life was determined on the basis of the flank wear on the tool. For the computer simulation of the search model, a .040" level of flank wear was specified as the "tool life". This amount of wear is often considered as a tool life cutoff point. However, in the machining phase of the research it was found that a .040" level would require a great amount of time in order that the verification of the search method could be completed. For this reason a .015" level of flank wear was considered to be the wear cutoff point for tool life.

4. Surface Finish Penalty Cost

A number of penalty costs were considered and tested. The effect of varying the penalty cost on the computer search can be seen in Figures 15 to 17, and is discussed at a later time in the results section of the study.

SURFACE FINISH PENALTY COST OF $.25 PER DEFECTIVE

CONDITIONS:

Method of Steepest Descent
Five point test pattern
Four replicates/point

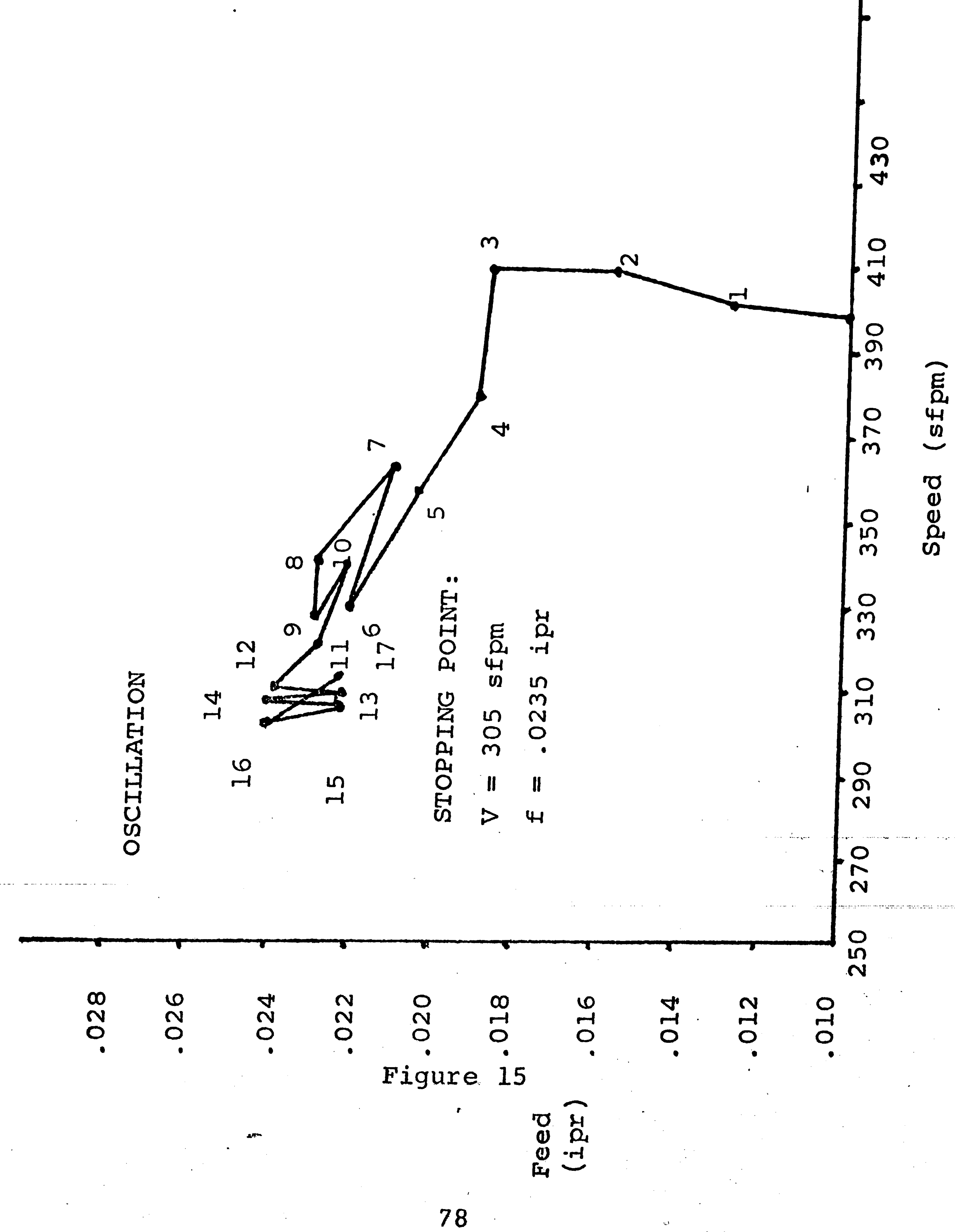


Figure 15

SURFACE FINISH PENALTY COST OF $5.00 PER DEFECTIVE

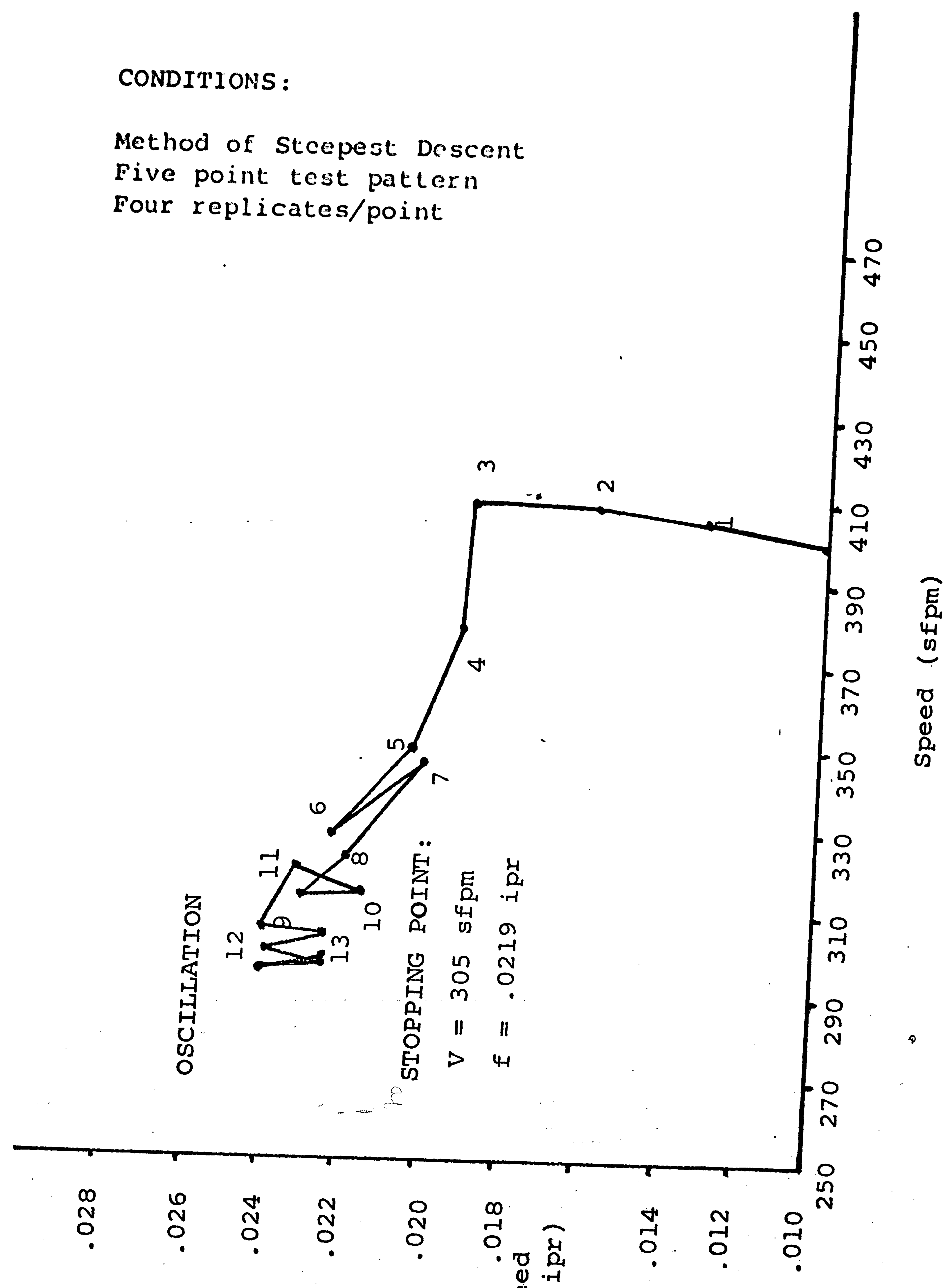


Figure 16

SURFACE FINISH PENALTY COST OF $10.00 PER DEFECTIVE

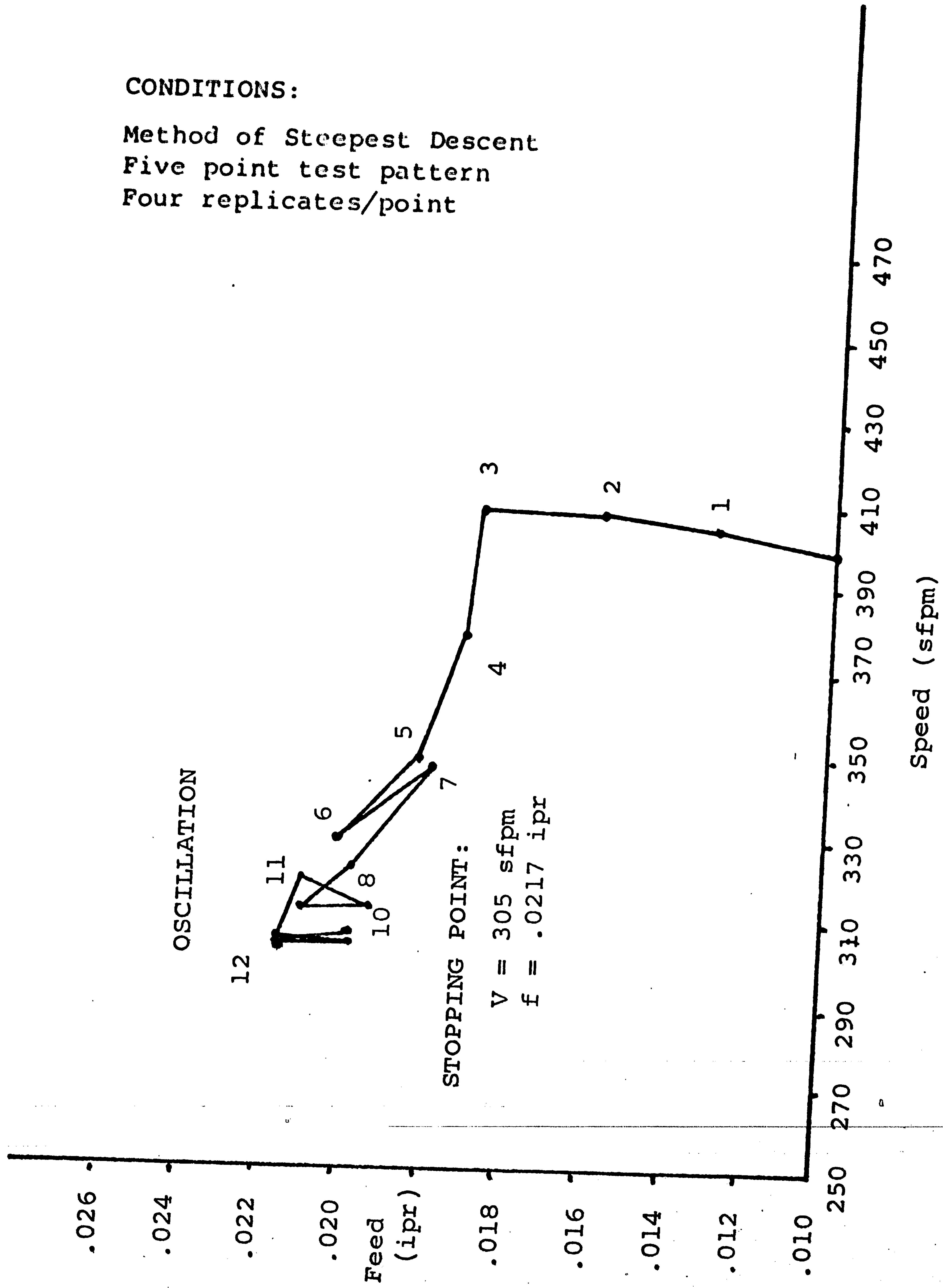


Figure 17

5. **Test Point Pattern**

In the portion of the study concerning the description of the experiment, 3 test point patterns were presented for evaluation: 1) Face-Centered; 2) Four Point; 3) L Pattern. These are shown in Figure 18 with the meaning of the term "test point distance" defined for each pattern. The selection of a pattern is a significant matter and should be a compromise between two few points which decreases the time to evaluate the index at each step and to collect appropriate data but sacrifices accuracy, and too many points which has accuracy but at the expense of too long an evaluation and collection time. Figure 19 contrasts the three test point patterns by showing three simulated searches under identical conditions except for test pattern used.

6. Number of Repetitions at Each Test Point

The determination of the number of repetitions to be taken at each set of cutting conditions in the test pattern is significant since the decision will again reflect the compromise described in selecting the number and arrangement of points in the test pattern. As mentioned

TEST POINT PATTERNS

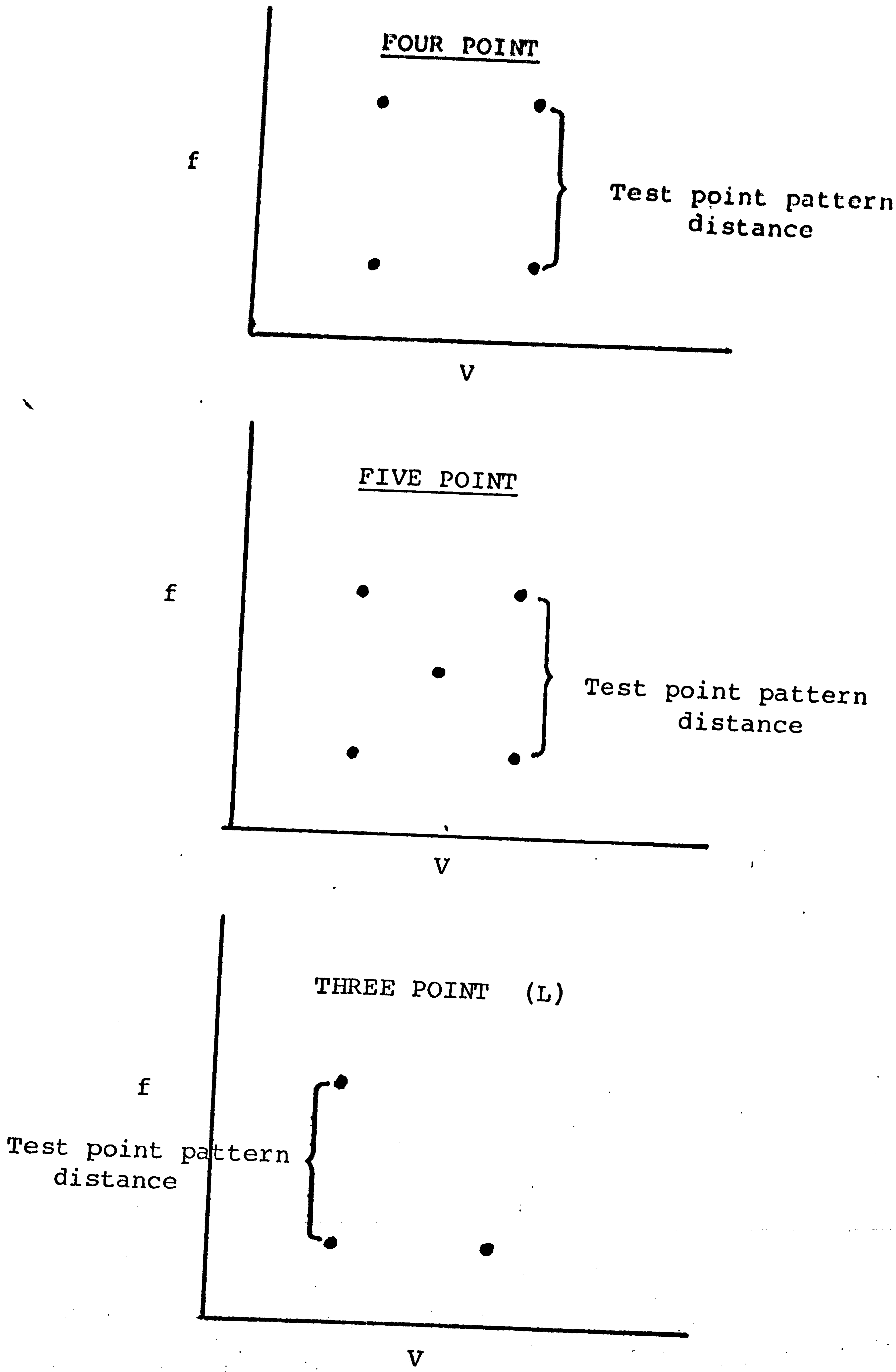


Figure 18

COMPARISON OF TEST POINT PATTERNS

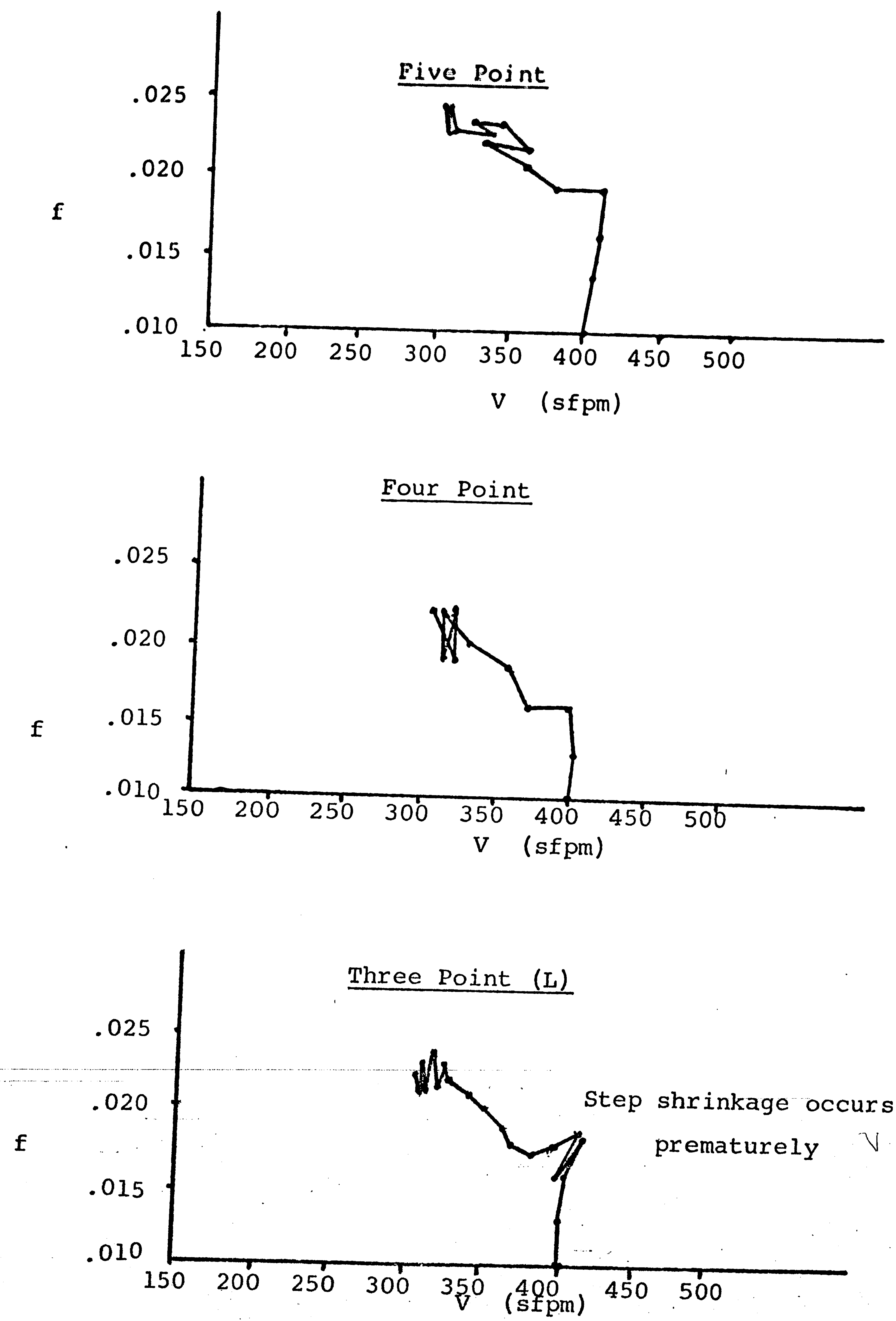


Figure 19

earlier, repetition of each set of cutting conditions is necessary due to the variability in the machining operation. In this research, the level of flank wear (and ultimately, tool life) and surface finish were measured for several tools operating at the same cutting conditions. Therefore, an average of these values, should provide a good measure of the value of the process variable which is used to evaluate the index of performance. Figure 20 shows the effect of different number of replications per test pattern point on the computer simulation search. One to eight repetitions were considered in the simulation phase of the study.

7. Variation

The computer simulation model is accurate only if the appropriate variability is included in the flank wear and surface finish models. However, it should be determined whether the model results differ substantially with or without variability included. If there is no substantial difference, then the number of

COMPARISON OF FOUR AND EIGHT REPLICATES PER TEST POINT

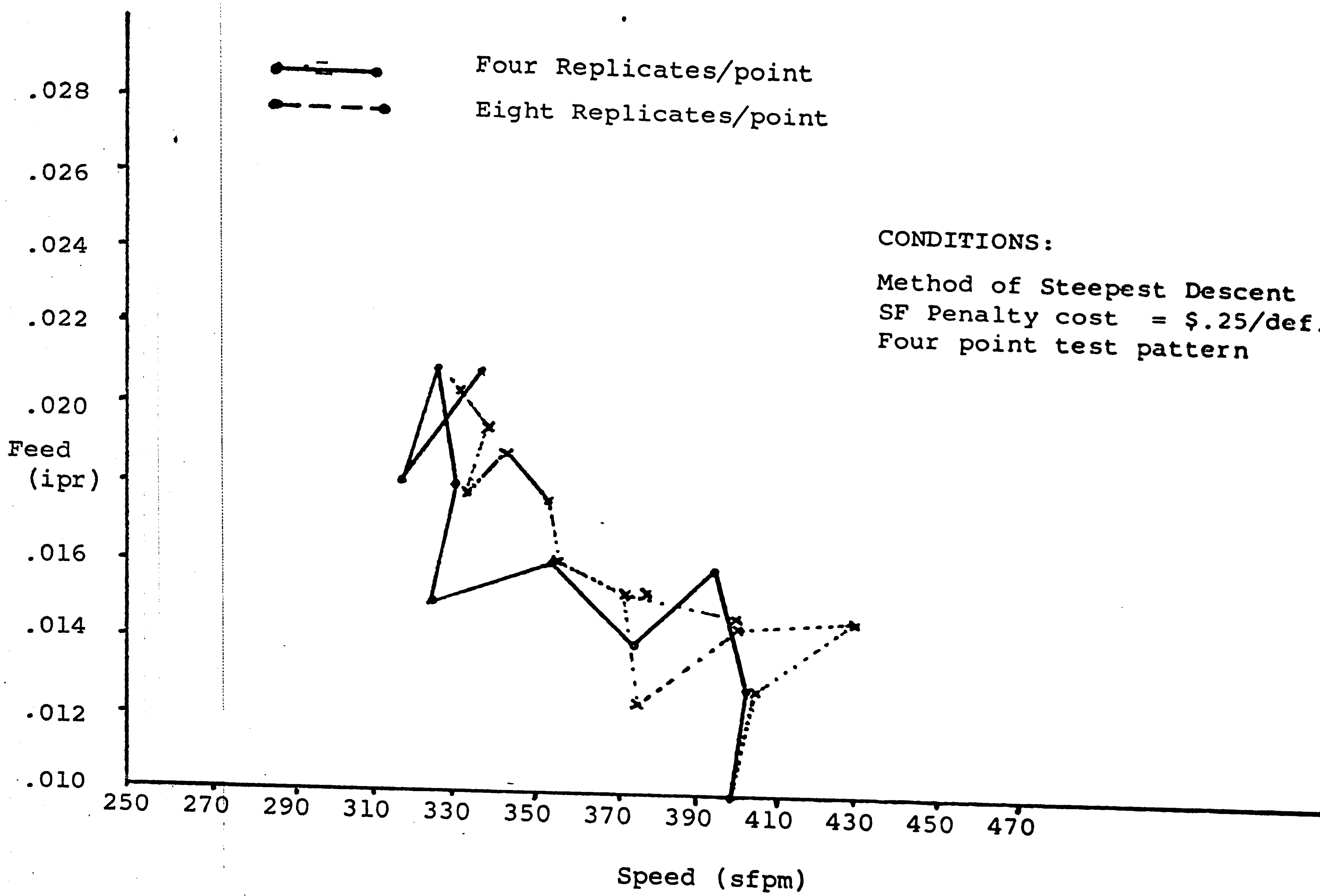


Figure 20

replications question would no longer be germane. A comparison of searches with and without variability included is shown in Figure 21. All other conditions are identical.

8. Starting Point

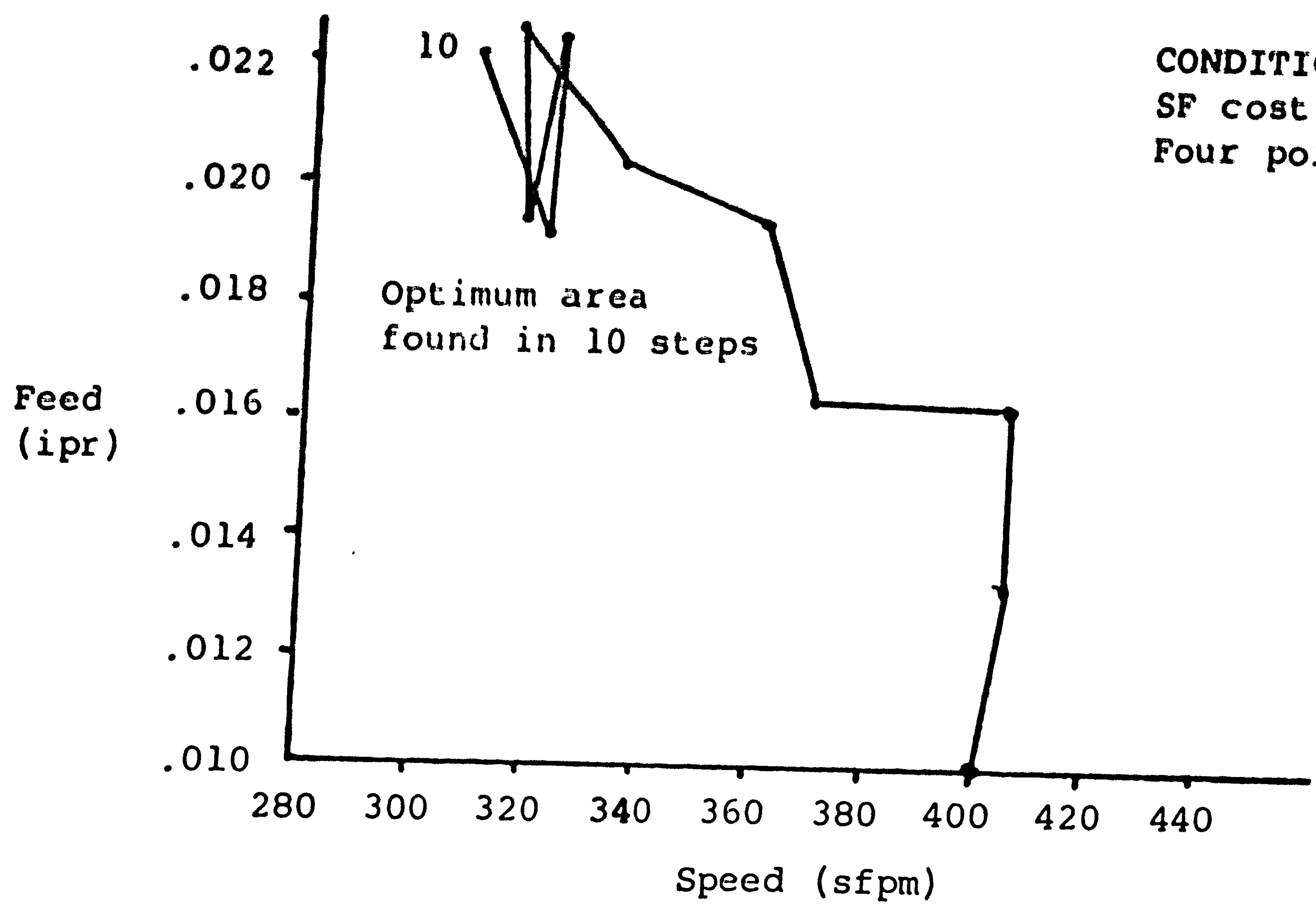
Although any starting point for the search should lead to the same "optimum" cutting conditions for minimum cost, the starting point does affect the time to reach these improved cutting conditions. In applying a self-adaptive search procedure as suggested in this research, the most likely starting conditions would be those specified in various machining handbooks. For this reason, Volume 3 of The Metals Handbook was used to provide starting conditions for the particular tool-work combination used in the study.

9. Step Size and Test Point Pattern Distance

The size of the step taken determines in part the time required to reach the optimal condition area. A

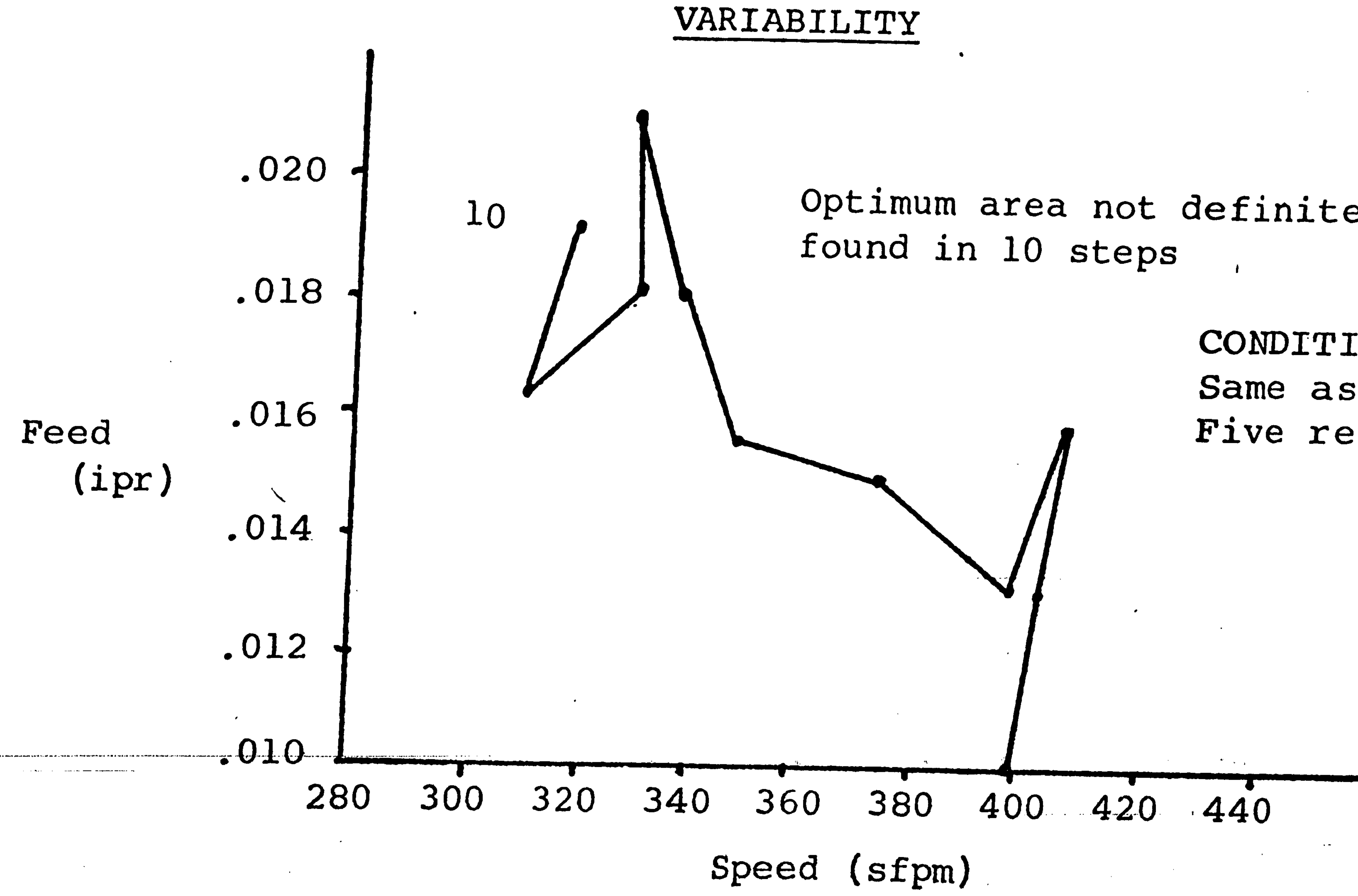
COMPARISON OF SEARCH METHOD WITH AND WITHOUT VARIABILITY INCLUDED

NO VARIABILITY



CONDITIONS:
SF cost = $.25/dcf.
Four point pattern

VARIABILITY



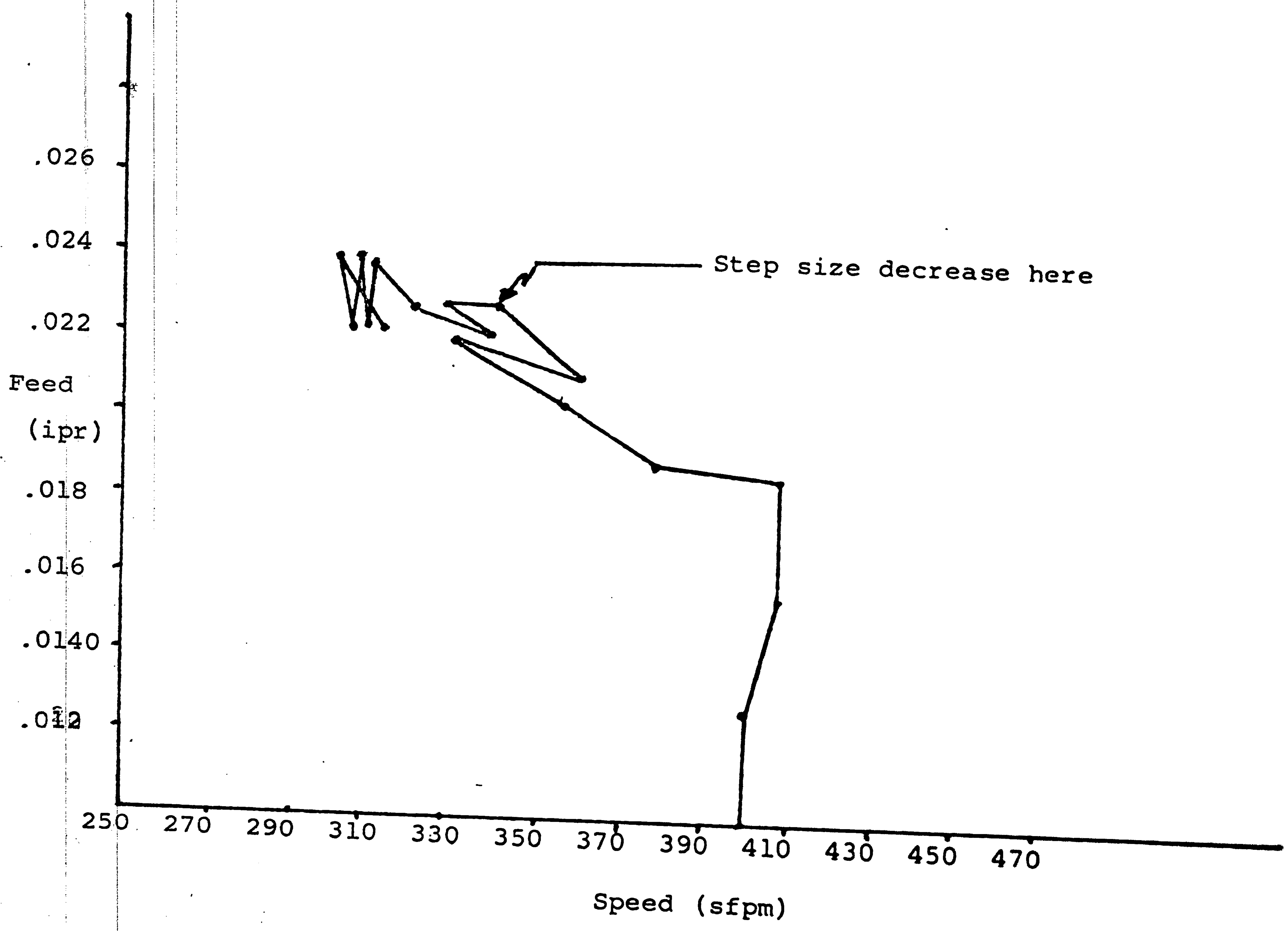
CONDITIONS:
Same as above but
Five rep's./point

Figure 21

variable step size scheme is particularly desirable since it allows larger steps at cutting conditions a substantial distance from the optimum set and smaller steps as the machining conditions approach the optimal area. Step size also reflects test pattern point distance since the greatest step which can be taken results in a move to the perimeter of the pattern. Therefore, by decreasing the point separation, the step size is also decreased in the same proportion.

Although several variable step size schemes were considered, the most successful one applied the following strategy. If the signs of the gradient components in both the speed and feed directions change two times successively, the test point separation and the step size were reduced by one half. This was done in an attempt to fine tune the search when the area on the speed-feed response surface was found in which the optimum probably lies. Thus, a more intensive search was performed in the optimum area. Figure 22 shows a simulation search using the strategy described.

Figure 22



SAMPLE OF STEP SIZE CHANGE

10. Stopping Criteria

A characteristic of any search technique is the inability of the method to proceed to the optimum point and stop there. Most methods prevent constant overstepping of the optimum by developing stopping criteria. A common criterion is as follows: If improvement of the index of performance is less than some prescribed level for a certain number of steps, then the search should be ended. A similar criterion is that if the signs of the gradient components in the feed and speed direction change successively a certain number of times, then this should indicate persistent overstepping of the optimum and the search should be ended. Figure 23 demonstrates this overstepping which should lead to the end of the search.

It is clear that time would not permit all of the 10 areas to be thoroughly investigated. In some areas, decisions were made to limit the amount of time and money spent in computer simulation. Thus, the results presented do not attempt to relate the best way to develop a self-adaptive procedure based on search technique, for this matter

SAMPLE OF OVERSTEPPING

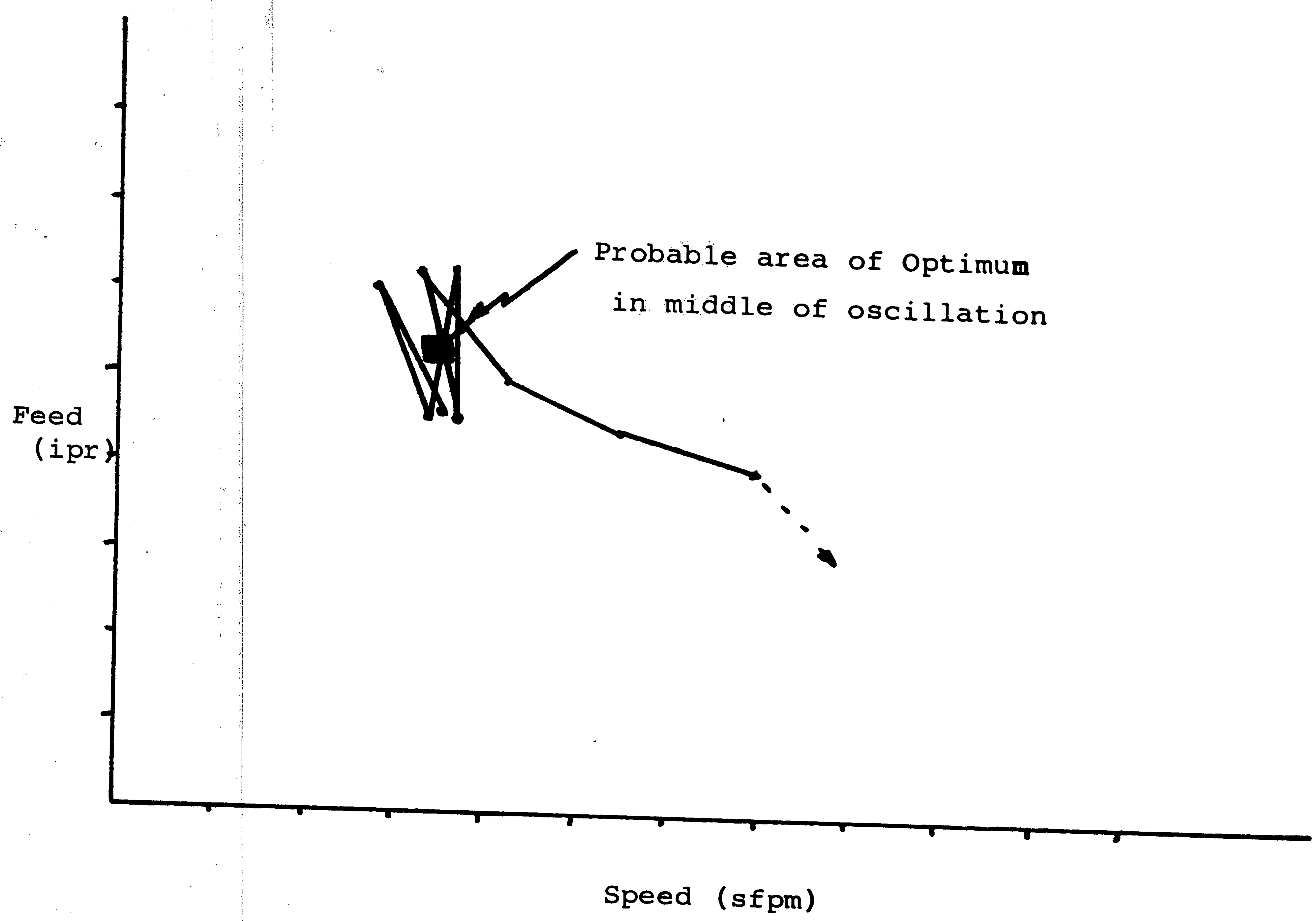


Figure 23

would be in many cases unique to the particular machining operation performed and the objectives of management. However, the results do present a way in which a self-adaptive procedure can be developed and shed light on the problem areas which must be adequately answered.

Results

For reasons described in previous sections, the investigation to determine a suitable search technique for a self-adaptive procedure has been limited to two types of gradient searches having minimum cost per piece (per cubic inch) as the machining index of performance. A tool life criterion has also been established as .040" flank wear for the computer simulation phase.

Method of Search

In comparing the two gradient strategies, it was found that the method of steepest descent was more efficient in all simulated searches observed. Efficiency is assessed quantitively by the number of steps to the stopping criterion and qualitatively by the directness of the stepped route to the optimum cutting conditions. The improved efficiency of the method of steepest descent should be expected since the method moves in the direction prescribed by the gradient components. On the other hand, the variation method can only move to one of the points in the test pattern and is, therfore, constrained in direction and length of movement. To illustrate this result, Figures 24 through 25 are provided to show some comparisons of the two methods.

Test Point Pattern

Among the three patterns tested, the face centered and four point patterns consistently offerred improved efficiency over the L pattern. This could be explained by the fact that the L pattern only has three points from which to estimate the gradient components. The L thus, suffers from inaccuracy which is substantial enough to mislead the search strategy and eliminate it from further consideration. Figure 26 clearly shows the problem in a comparison of the three test patterns.

Figure 27 also shows the similarity of the paths determined by use of the face centered (5 point) and the four point patterns. This was typical of nearly all attempts made to contrast these two patterns. Since no substantial gain could be seen from using the five point scheme the four point pattern is recommended since it is capable of nearly identical results but with fewer test points. Fewer test points imply a shorter and less costly search.

COMPARISON OF METHOD OF STEEPEST DESCENT AND VARIATION METHOD

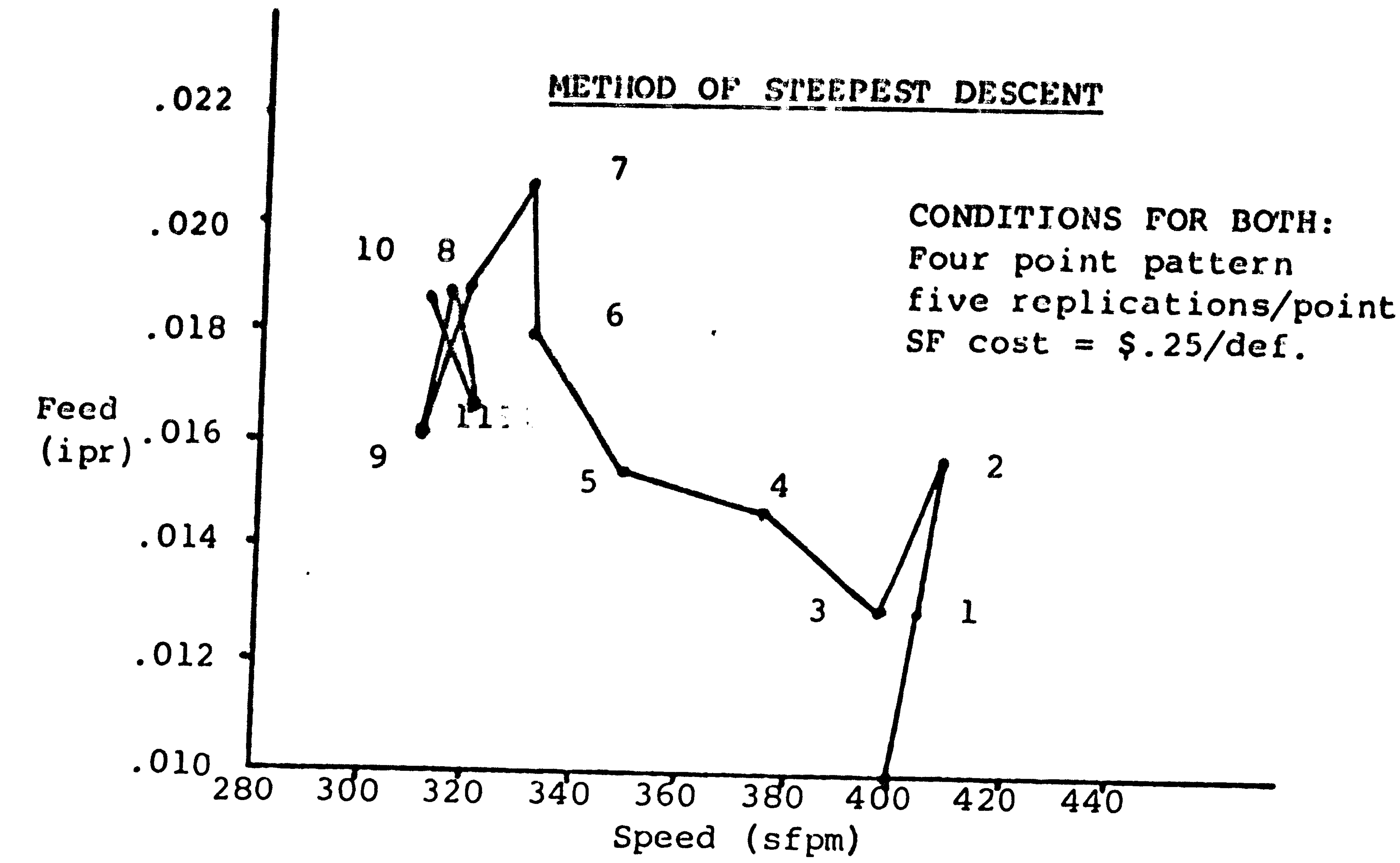


Figure 24

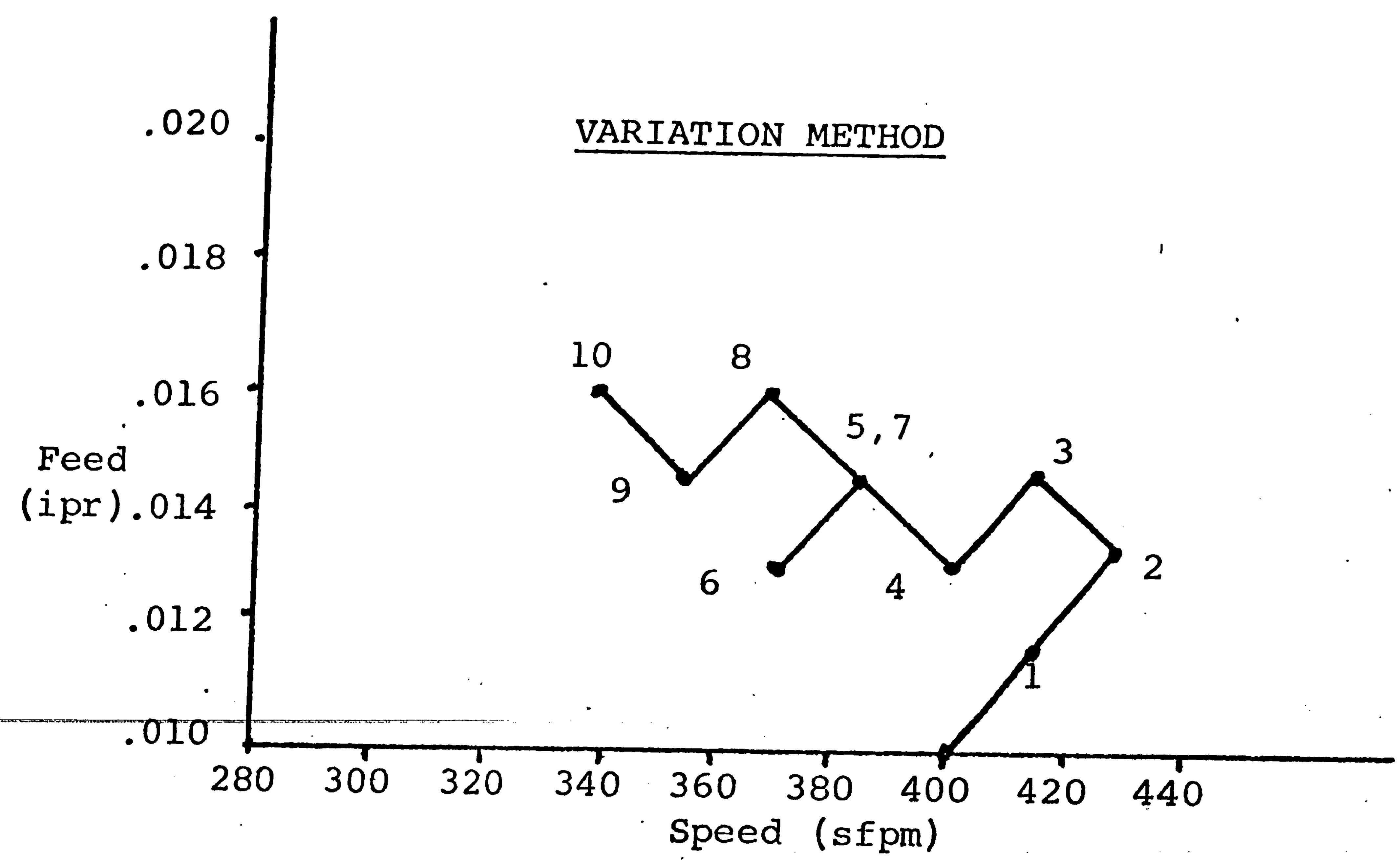


Figure 25

COMPARISON OF TEST POINT PATTERNS

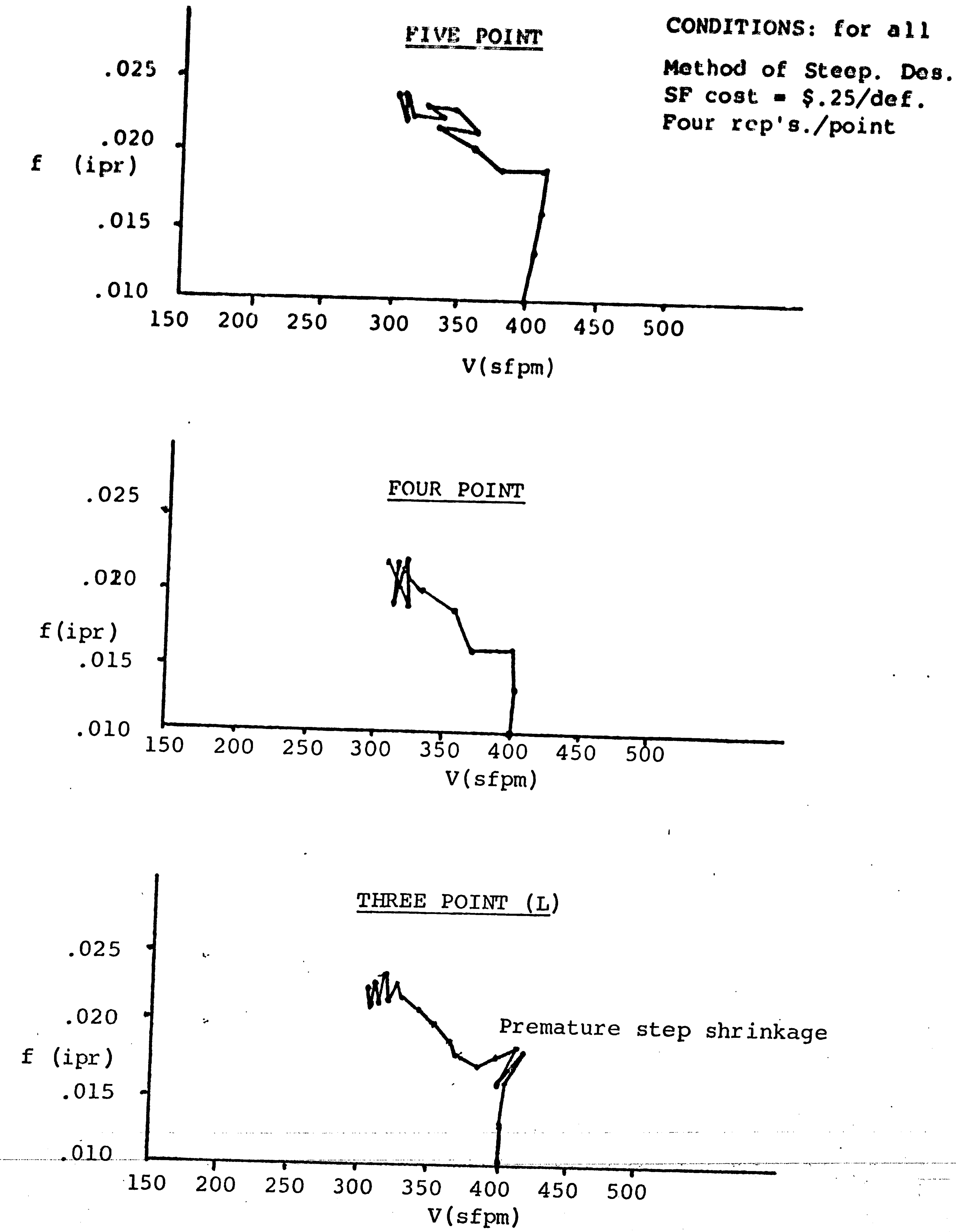


Figure 26

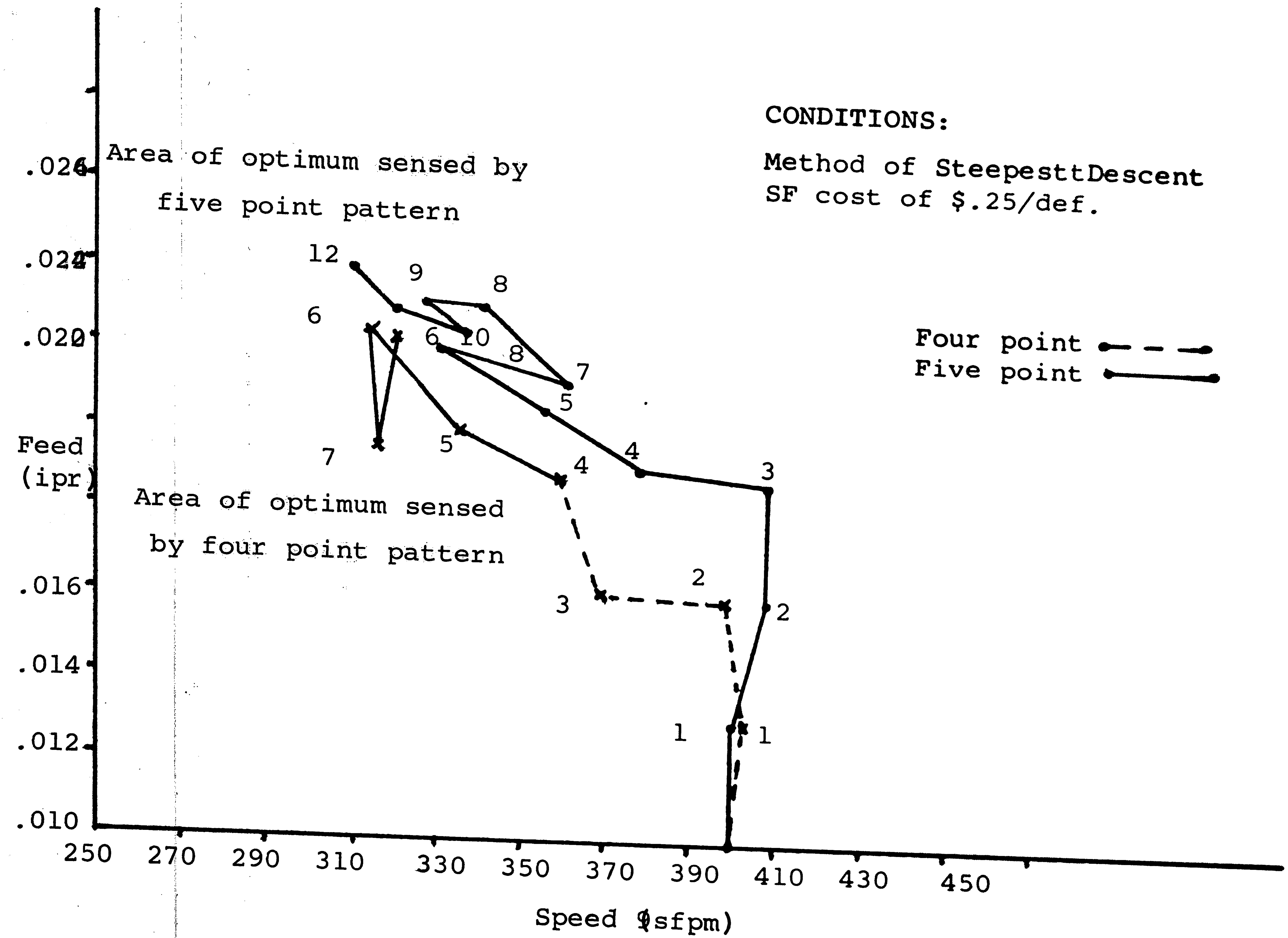


Figure 27

COMPARISON OF SEARCHES USING FOUR POINT AND FIVE POINT PATTERNS

Number of Repetitions at Each Test Point

This matter was given attention in both the computer simulation phase and the machining verification phase. As mentioned earlier, from one to eight repetitions were considered in the computer simulation phase. Figure 28 clearly shows that more than one replication is necessary with the variation present. In all cases tested, a search based on the single evaluation of the index of performance at each test point resulted in inefficient circular paths which often could not reach the optimum area. On the other hand, it was found that five through eight replications did not substantially improve on the results provided by four repetitions per set of cutting conditions. Therefore, the suggested number of replications observed in the computer simulation phase was two to four.

Step Considerations and Stopping Criteria

In the computer simulation phase it was decided to use steps of such a length that a move was always taken to the perimeter of the test pattern. There is no point in moving a smaller distance than this and a larger distance was considered unjustified since the new origin would lie outside of the area tested. Once the search

INEFFECTIVENESS OF THE USE OF NO TEST POINT REPLICATES

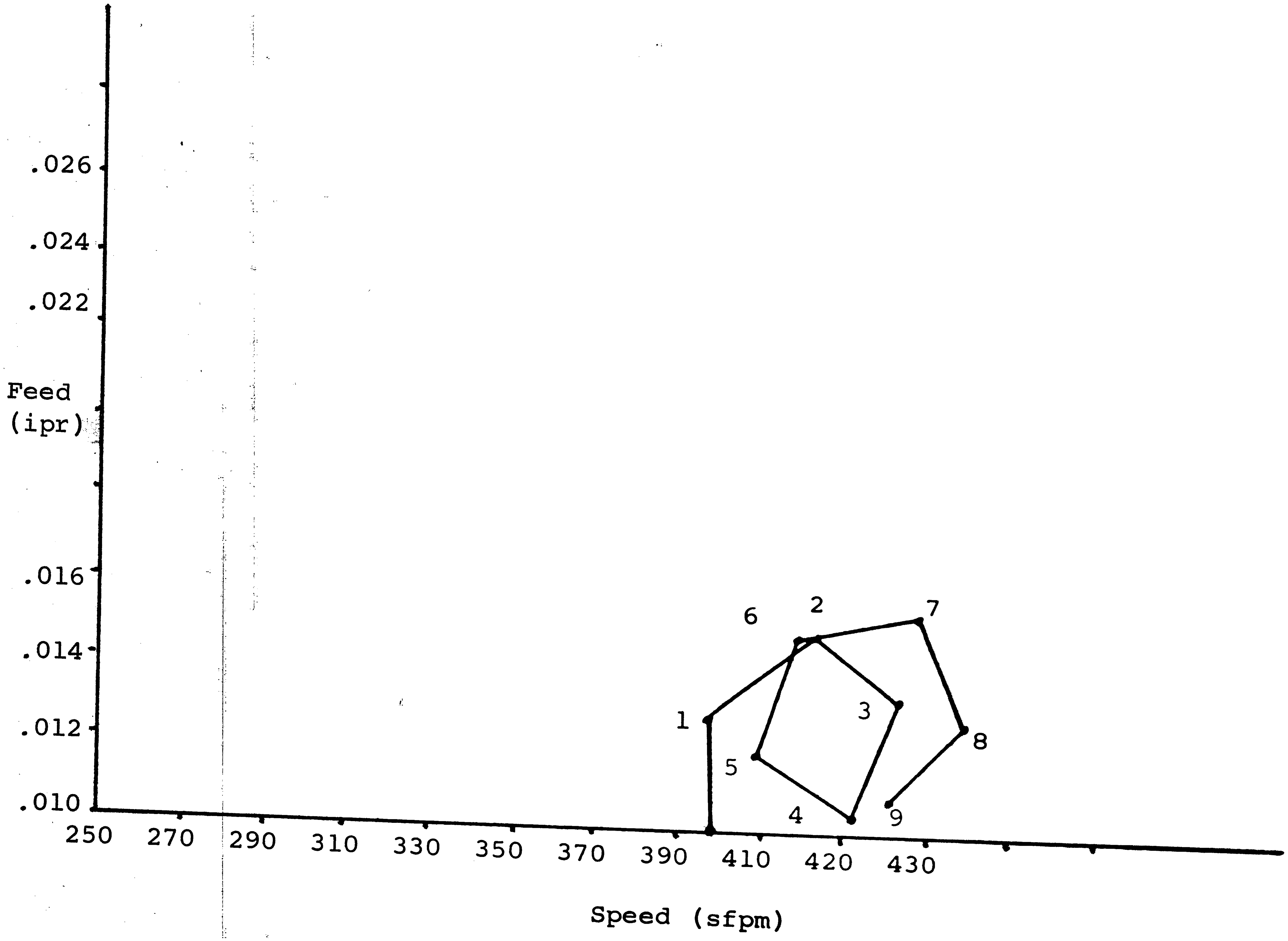


Figure 28

98

approached the area, in which the optimum cutting conditions could be found, it is desirable to decrease the test point separation and step size to search the optimum area more intensively. Many methods capable of sensing the optimum area exist but two were tested:

1. If the signs of the gradient components change on two successive steps, then decrease the test point separation and step size by one half.
2. If a certain per cent improvement in the index of performance is not attained on two successive steps, then reduce the test point separation and step size by one half.

It was found that the first method suggested was very reliable in sensing the area of the optimum. Good results were obtained using this technique. The second method was unacceptable and could not be relied upon. Many times the optimum area was sensed prematurely resulting in the decreasing of step size at an inappropriate time. An example contrasting the two means and demonstrating the problem encountered with the use of the second technique is found in Figure 29.

The stopping criteria which was most successful in the computer simulation phase was that the search would end if both gradient components

Comparison of two methods of Decreasing Step size Near The Optimum Area

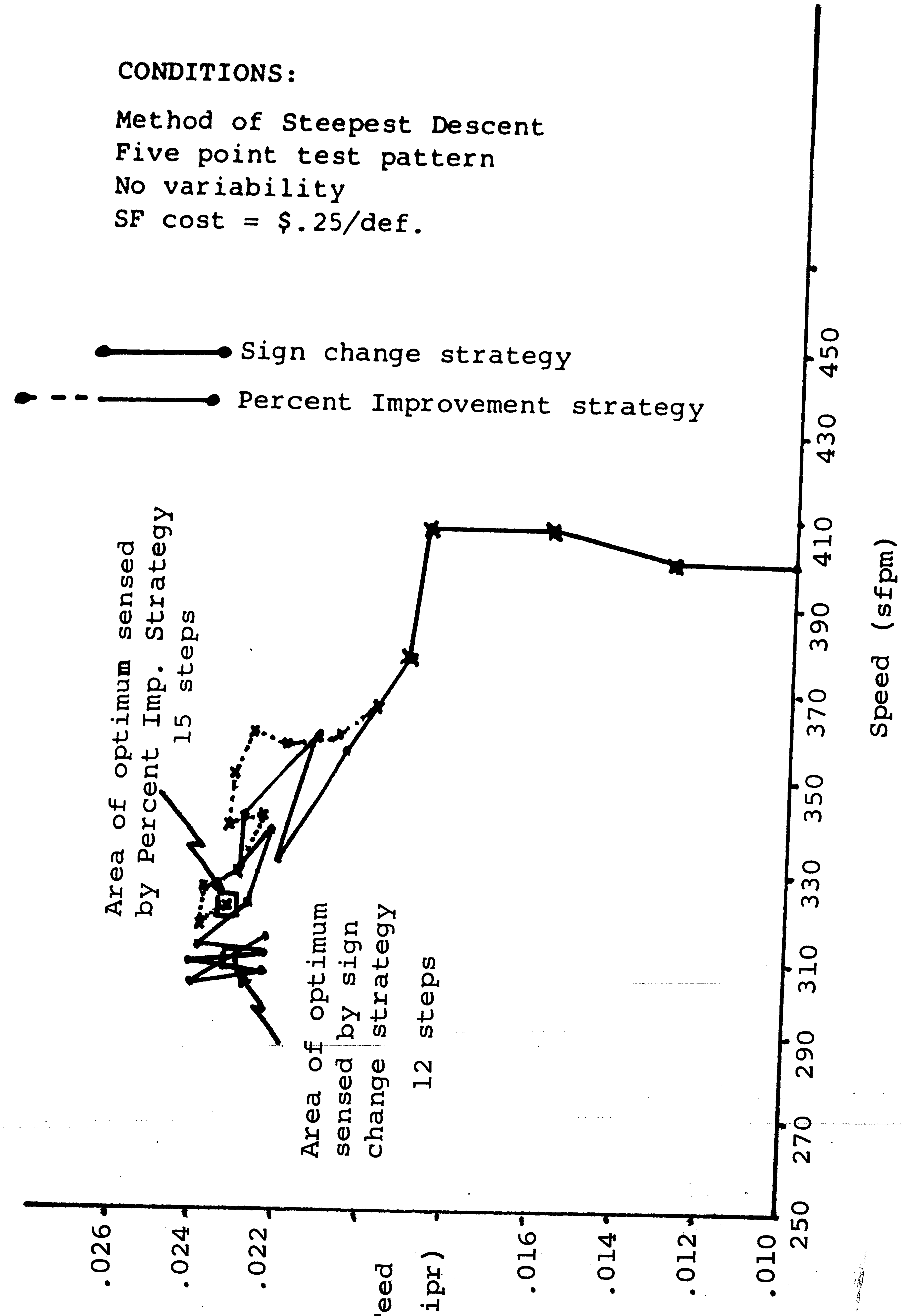


Figure 29

changed in sign on four successive steps once the step size had been decreased by one half. The optimum cutting conditions would then be specified as those which resulted in the smallest cost per piece of the two sets of cutting conditions evaluated at the origin and the endpoint of the final step.

Surface Finish Penalty Cost

The assignment of a dollar value representing the penalty cost incurred for exceeding the surface finish specification is unique to the type of operation performed. This cost would vary depending on whether the piece could be reworked or not, the rework cost, the value of the material, and the cost of previous machining or working time. Several penalty costs ranging from \$.25 to \$10.00 per defective were considered and tested. The search model reacted as expected in that higher penalty costs resulted in more conservative optimal cutting conditions. Figure 30 reveals identical searches with the exception of penalty cost incurred. The search was found to be most successful as far as determining minimum cost cutting conditions for low penalty cost values (i.e. \$.25 to \$1.00/defective)

COMPARISON OF THE VALUES OF SURFACE FINISH PENALTIES

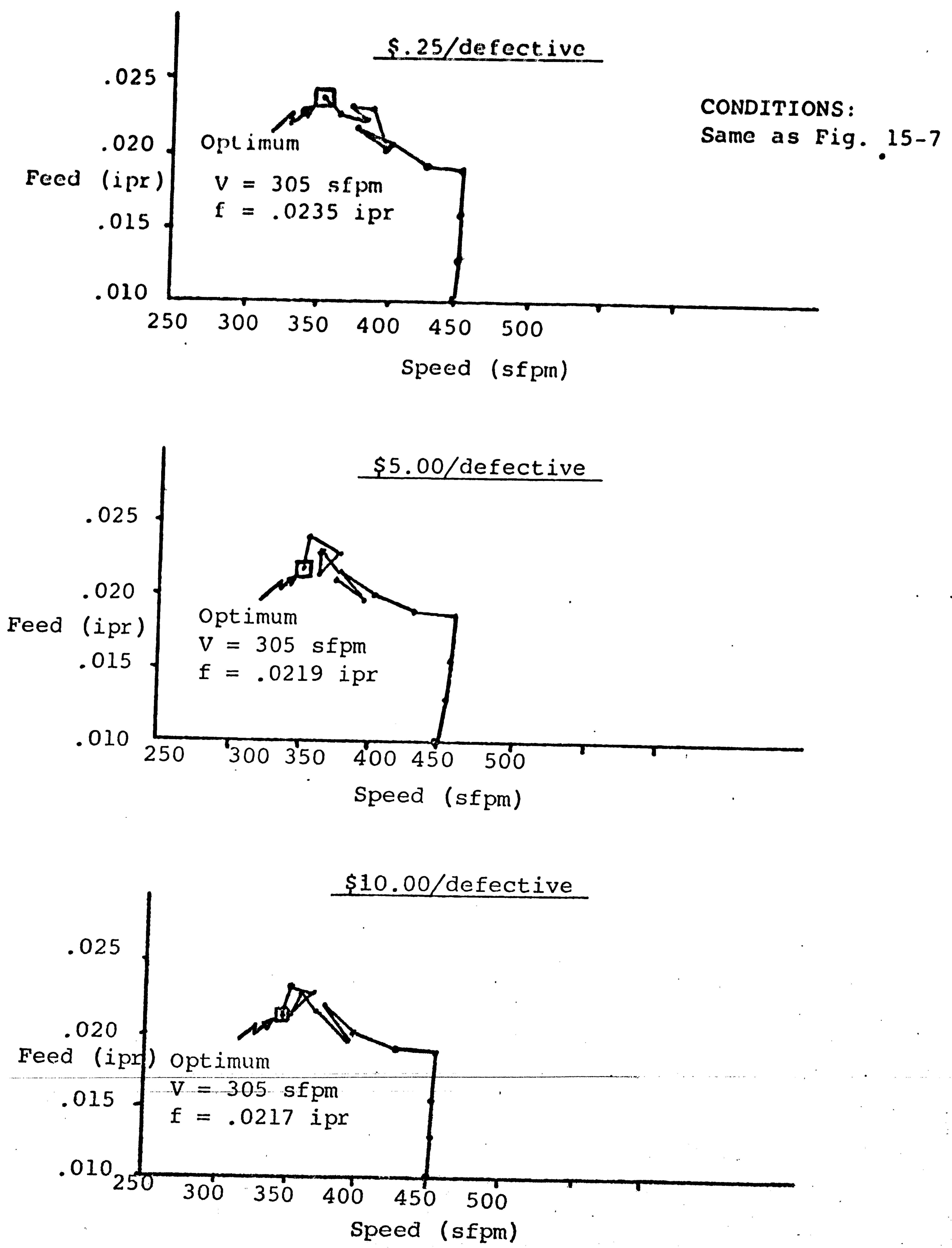


Figure 30

Comments on the Results of Phase II

The computer simulation of the application of an optimum seeking procedure to machining condition improvement allowed substantial study of the self-adaptive approach to be performed without expensive machine shop data collection and testing. On the basis of results found in the simulation phase, many of the broad indefinite areas of study mentioned earlier were narrowed to smaller, more manageable research areas. Although the computer simulation of the study was useful, it was necessary to test the optimum-seeking procedure under actual machining conditions. For this reason, Phase III of the research used the search stragegy developed in Phase II, and refined the procedure as dictated by laboratory machining results.

Phase III: Machine Shop Validation

The gradient search technique described in Phase II was applied to an actual machining set-up in the final phase of the research. The purpose of the metal cutting was to determine if the results of the computer simulation could be accurately and feasibly applied to an actual production situation. As in Phase I, machining was performed in the Manufacturing Processes Laboratory. The experimental procedure, tooling, and work material were identical to that described in the section of the thesis concerning Phase I. For this reason, the machining details need not be related again at this point.

The machine shop validation phase consisted of several optimum-seeking searches performed in the following manner:

1) Starting conditions were selected from Volume 3 of the Metals Handbook and were based on the work material and its hardness and the depth of cut required. As in Phase I, a .075 inch depth of cut was maintained. The cutting conditions recommended for S.A.E. 4340 with a hardness of 30 to 35 R_c and a depth of cut of .075 inch were: V = 300 sfpm; f = .0152 ipr.

2) A pattern of test points surrounding the starting point were established and the corresponding cutting conditions of the points were recorded on a data sheet. A sample of the sheet can be found in Appendix C. The four point pattern was chosen for the machine shop validation phase due ot its satisfactory performance in the computer simulation.

3) The pattern of cutting conditions was tested by machining at each test point successively until the tool life criterion was exceeded. In Phase III tool life was based on a flank wear level of .010 or .015 inches. The degree of flank wear describing tool life was decreased substantially in the machining phase from the .040 inch level previously considered in order to decrease the amount of machining time. During cutting at each of the four test points, flank wear and surface finish were measured at two minute intervals.

4) Machining was repeated for the same test pattern in order to obtain replicates. Thus, Step 3 was repeated as many times as needed.

5) Given the tool life and surface finish data from the replications, the average value of the index of performance was calculated

for each of the cutting conditions in the test pattern. Then, the gradient components for feed and speed were determined and the appropriate step taken. The method of steepest descent was used to direct the steps of the search. Step size was as described in Phase II. A computer program was written to take the cutting data concerning tool life and surface finish as input and produce the appropriate step as output.

6) The entire process (Steps 2 through 5) was repeated until some stopping criteria were reached.

Index of Performance Considerations

In the machine shop validation phase the method of steepest descent with minimum cost objective was used exclusively as the search strategy. However, even though cost per cubic inch of material removed was the index of performance in all cases, four different means of determining this cost were investigated. Thus, it is actually appropriate to say that four different indices of performance were tested.

No. 1) The tool life criterion was established as .015 inch of flank wear. No penalty was incurred for exceeding surface finish specifications.

No. 2) The tool life criterion was established as .010 inch of flank wear. No penalty cost was incurred for exceeding surface finish specifications.

No. 3) The tool life criterion was established as .015 inch of flank wear. A standard surface finish penalty cost was determined for exceeding the surface finish specification during any one minute interval prior to the end of life of the tool.

No. 4) The tool life criterion was established as .015 inch of flank wear. A surface finish penalty cost was determined on the basis of the extent by which the specification during any one minute interval was exceeded. Thus, a surface roughness substantially greater than the specification would result in a higher penalty cost than a finish only a few microinches above the specification.

Several different indices of performance were considered to find an index which would respond suitably to the real economic effects of changing cutting conditions without the need for excessive replications. In addition, the amount of variation in the results caused by the selection of an index of performance was a reason for investigating a variety of indices.

The first two indices described both involve a tool life cost based on flank wear. Both have simplicity of usage as an advantage but the use of such indices may not be feasible in finishing operations. Thus, the scope of application may be limited unless some means of considering surface finish constraints is included. The use of an upper bound on the feedrate could overcome the problem of applicability in many cases.

The third and fourth indices offer another means of overcoming the surface finish constraint difficulty. Both indices involve a surface finish penalty cost which is incurred when the surface finish specification is exceeded. The third index mentioned charges a uniform amount regardless of how badly the specification is exceeded. Such a charge is probably realistic since rework charges would be nearly the same regardless of the extent of excess (within reasonable limits). However, such an index can often mislead the search. If a defective part, which is one microinch above the surface finish specification, is made at a particular test set of cutting conditions, the penalty cost is added to the total machining cost. ~~This set of cutting conditions, the penalty~~

~~cost is added to the total machining cost~~. This set of cutting conditions may be very close to the optimum set of conditions, but the new step taken will in all probability be drastically away from the point at which the defective occurred. Thus, it can be seen that the third index with a uniform penalty cost can over-react to cutting conditions which result in pieces only slightly above specifications.

The fourth index offers a variable penalty cost dependent upon the degree that the surface finish specification was exceeded. This index may not be as realistic, but should react in a reasonable manner when the specification is exceeded.

Number of Replications

The computer simulation phase recommended that two to four replications be made at each test point. The machining phase initially considered up to four replications as suggested.

Step Size and Strategy Considerations

As in the computer simulation, a test point pattern distance of 30 sfpm and .0030 ipr was tested. In addition, a search was considered with a point separation of 50 sfpm and .0050 ipr. Steps of uniform length were taken to the perimeter of the test pattern. The strategy by which the step size was decreased by one half when the signs of both gradient components changed twice successively was examined. Such sign changes generally imply that the search is overstepping the optimum and smaller steps should be considered.

Stopping Criteria

A procedure similar to that used in Phase II was considered to end the search at cutting conditions as close to the minmum cost conditions as possible. Essentially, if the signs of both gradient components changed four times successively, the search was concluded.

Other Considerations

Due to the success of the method of steepest descent in the computer simulation, other search strategies were not examined in the machine shop validation phase. The same comment can be made concerning the use of the four point test pattern exclusively in the final stage of the research. Surface finish penalty costs were arbitrarily assigned in the actual machining phase due to the dependence of such costs on material, previous operations on the piece, labor rates, overhead, etc.

Two complete searches were performed. The first search was defined by the following characteristics:

1) Method of steepest descent

2) Minimum cost objective

3) Four indices of performance. However, Index No. 1 guided the search.

4) Test point pattern distance of 30 sfpm and .003 ipr

5) Four replications per test point

6) Step size decrease according to sign switching strategy.

7) Stopping criterion according to sign switching strategy.

The second search examined the effect of increasing test point pattern distance to 50 sfpm and .0050 ipr. for a search with characteristics found to be suitable in the first search. The characteristics will be described in the result section.

Results

Figures 31 and 32 graphically show the results of the first and second searches attempted. Tables II and III of Appendix C present the graphical results of Figures 31 and 32 in Tabular form. The results shown can best be described by considering the areas investigated in each search and the conclusions reached from these results.

Search I (Figure 31)

Index of Performance

Figure 31 shows the operation of the method of steepest descent strategy using an index of performance (No. 1) based on a tool life criterion of .015 inch flank wear and no surface finish penalty cost. This index of performance was found to be superior to the three other indices in several ways.

1) Figure 33 shows the first step as recommended by the method of steepest descent based on each of the four indices. One would expect that the handbook starting conditions would be conservative with respect to the "optimum" feed and very close to the "optimum" speed. This result was seen to be true throughout the computer simulation as the search strategy

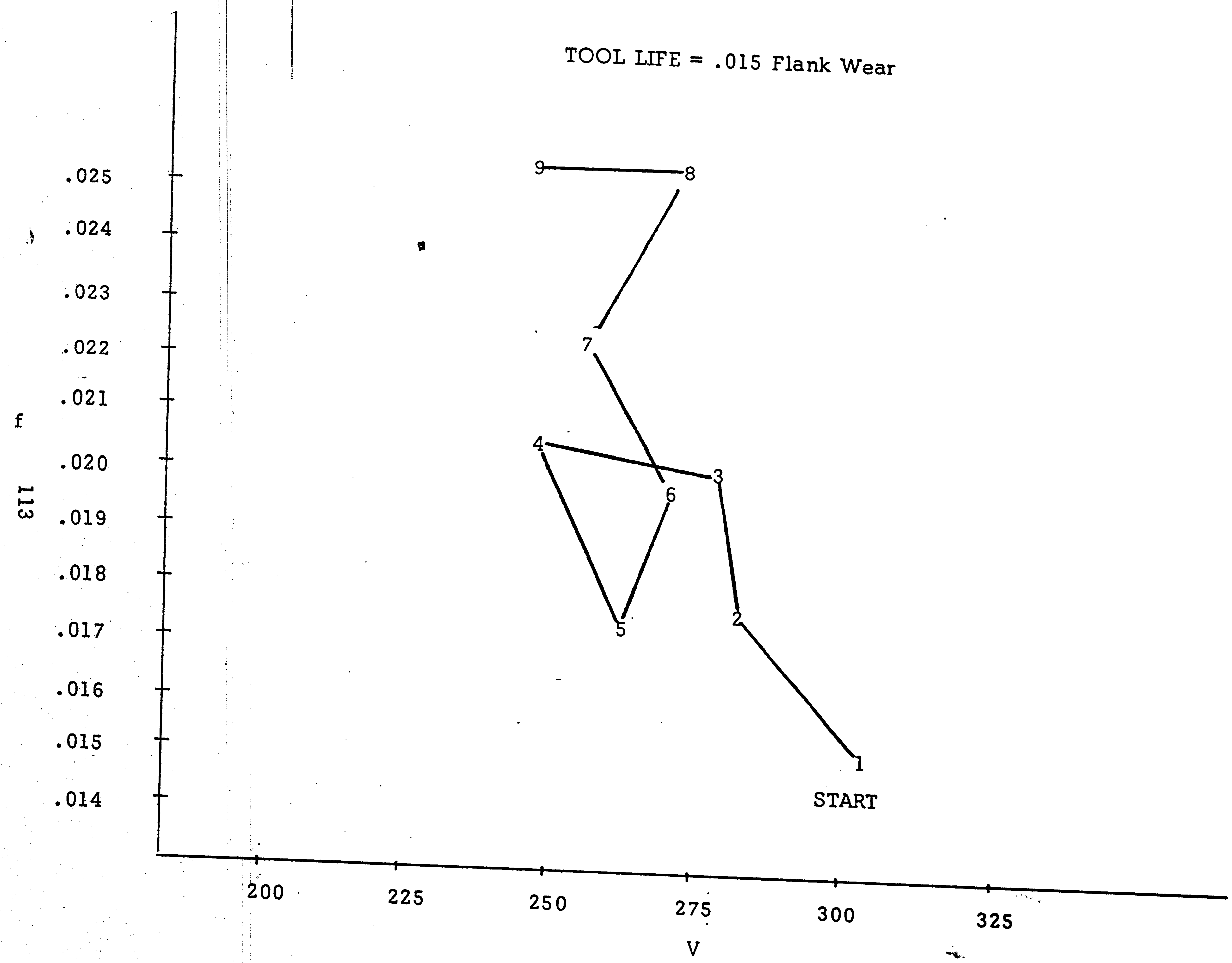

TOOL LIFE = .015 Flank Wear
.025
.024
.023
.022
.021
.020
.019
.018
.017
.016
.015
.014
f
1
2
3
4
5
6
7
8
9
START
200
225
250
275
300
325
V

FIGURE 31

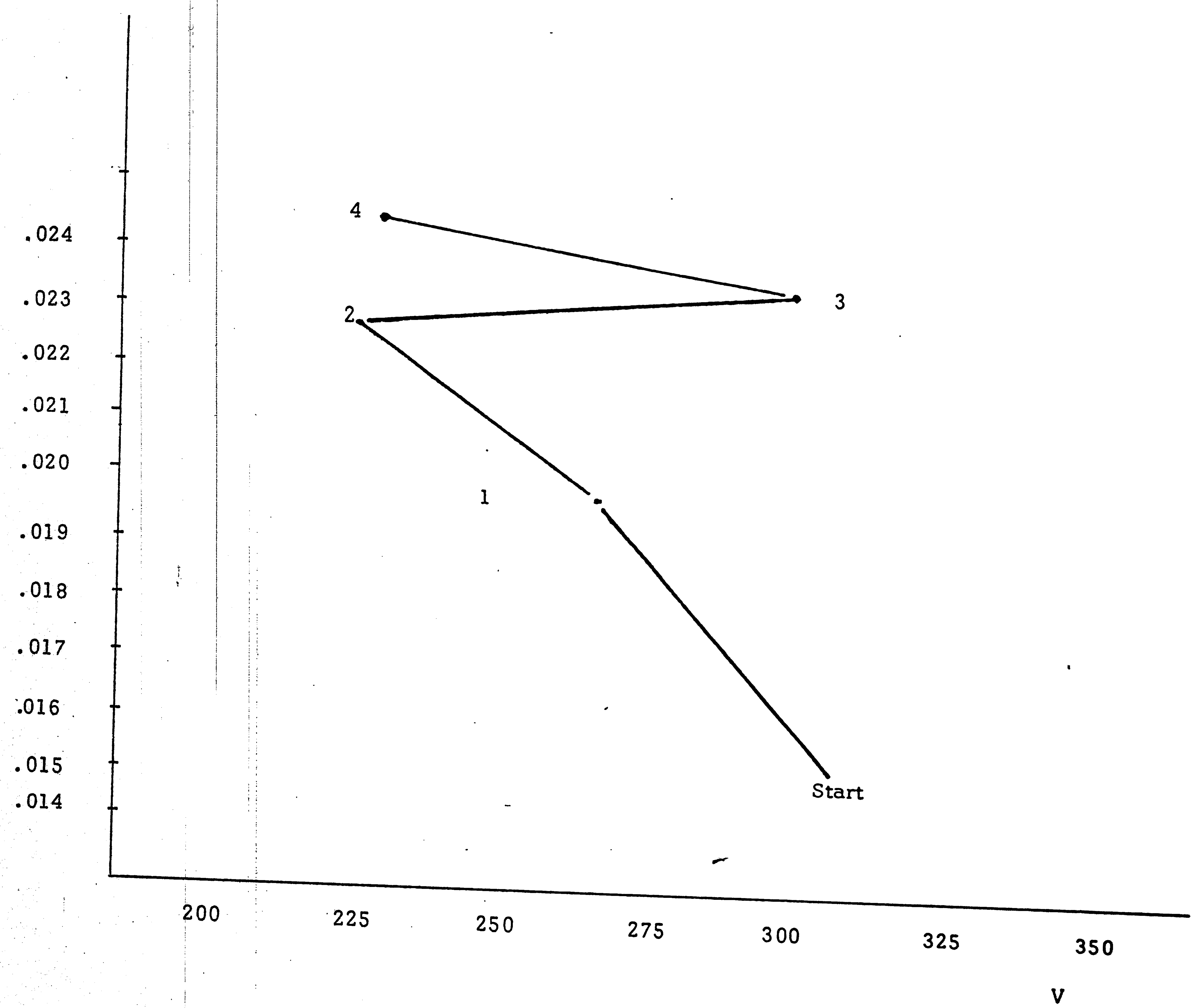

4
3
2
1
Start
f
.024
.023
.022
.021
.020
.019
.018
.017
.016
.015
.014
200
225
250
275
300
325
350
V

FIGURE 32

COMPARISON OF VARIOUS INDICES OF PERFORMANCE

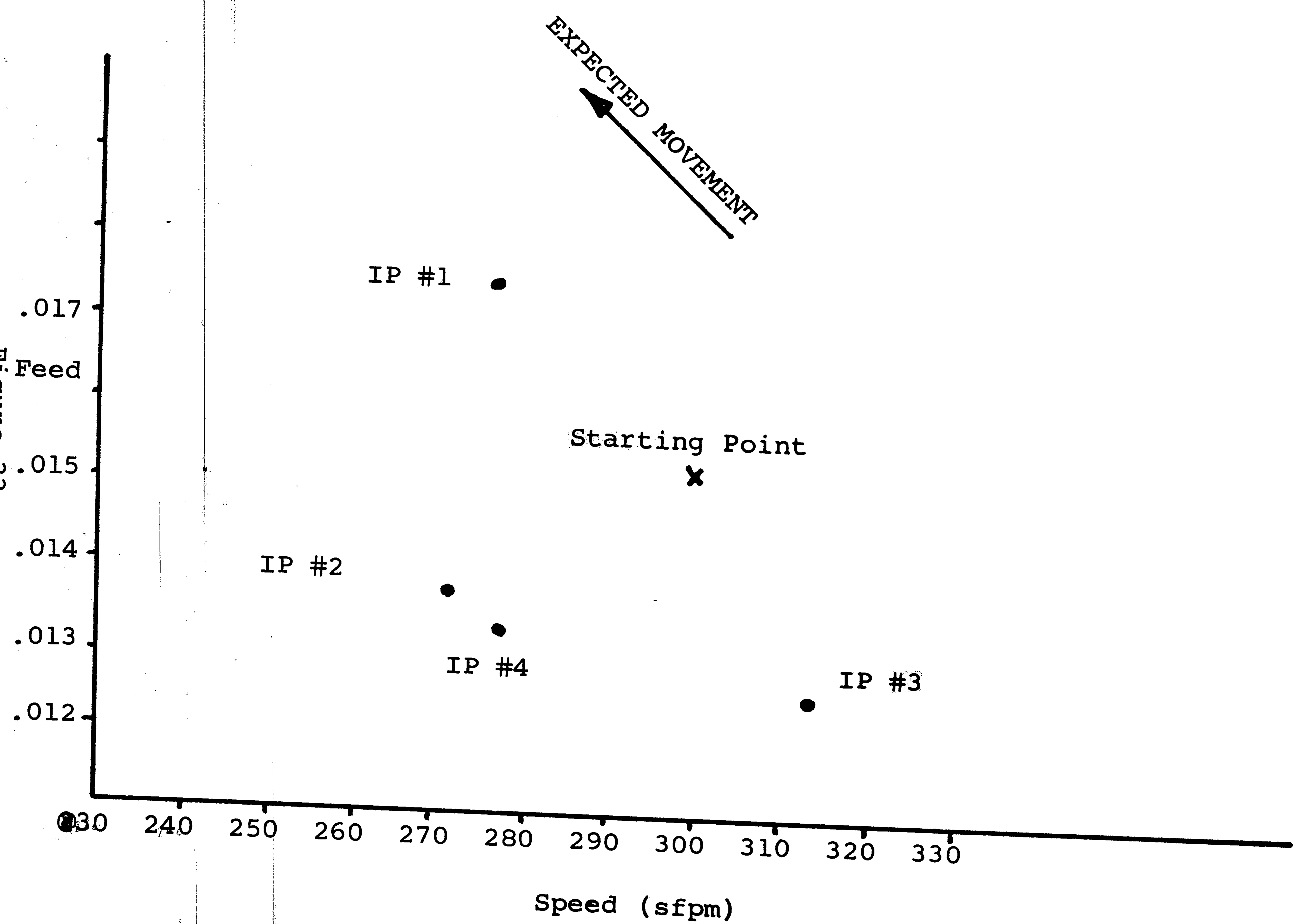


Figure 33

repeatedly moved the process from the recommended conditions to higher feeds and slightly slower speeds. For the cases where there was no surface finish penalty cost, the search continued to increase feed and decrease speed slightly. If a surface finish cost was levied, the search strategy reached a constraint as feed was increased and eventually, oscillated around a point close to the minimum cost conditions. However, regardless of the presence or absence of a surface finish penalty cost, the first few steps of the simulated searches were invariably found to increase feed and hold speed at nearly the same level.

Figure 33 shows that only for index of performance number one was the appropriate step made. The other indices of performance result in searches which are not as efficient. The explanation for the poor performance of the surface finish penalty cost indices (No. 3 and 4) may be that the surface finish variability was great enough to prohibit efficient operation of the search.

The variability of the surface finish data in the machine shop validation phase was larger than that used in the computer simulation phase. This can be seen through a comparison of surface finish data taken at a set of cutting conditions in Phase I with surface finish data for similar cutting conditions in Phase III. For example, in Phase I cutting was done at 300 sfpm and .0147 ipr. In Phase III cutting data exists for 300 sfpm and .0152 ipr. These two data sets and others can be compared to examine the variability present in each case. Figure 34 presents the two data sets.

Phase	V	f	SF / time	1	2	3	4	5	6
I	300	.0147		90	93	100	99	101	
III	300	.0152		155	140	135	135	140	

Figure 34

Clearly, for similar conditions a wider range of variability exists in the Phase III surface finish data, and this is found to be the case when other data sets are compared. If more variability was indeed present during the machine shop validation phase, more replications may be required than the number of replications suggested by the computer simulation. (The simulation was based on Phase I data and an index of performance including surface finish penalty cost was found to perform well in the simulation with two to four replications). This logic leads to the second reason that an index of performance without a penalty cost was found to be superior to an index which included such a cost.

2) Due to the wider degree of variability in surface finish data in Phase III, more replications would be required to permit a surface finish penalty cost index to be used with reasonable efficiency. Replications, however, are costly and time consuming. The index with a tool life criterion of .015 inch of flank wear and no penalty cost has a substantial advantage in that an efficient search was obtained with only two replications. When the tool life criterion was decreased to .010

inch of flank wear, atleast four replications were required to produce a somewhat efficient search.

For these reasons, the index of performance with a tool life criterion of .015 inch of flank wear and no surface finish penalty cost was selected as the best of the indices tested. For application in a finishing operation with a surface finish specification, such an index would have to be optimized within a certain feed range to prevent the search strategy from moving the operation to an excessive feed rate. Without such a constraint the search would continue to increase feed rate. Figure 31 shows the result of an unconstrained search.

Number of Replications

Figure 31 shows the results of a search in which two replicates were collected for each test point. The efficiency of the search suggests that 2 replicates are sufficient for a method of steepest descent strategy based on the index of performance selected. (No. 1).

Step Size and Strategy Considerations

In Search I, a test point pattern distance of 30 sfpm and .0030 ipr was used and was found to be satisfactory. However, a larger step size resulting from an increased test point separation may have avoided the difficulty seen in steps 4 through 6 of the search shown in Figure 31. Apparently, the machining variability was quite extensive at point 4 causing a step in the wrong direction to be taken. The problem was a local one and the search quickly proceeded on a more appropriate course. A larger step may have been able to move past this problem area.

In addition, a larger test point separation and step size could help overcome a second difficulty encountered when feeds of only .0030 separation needed to be set on the machine. Often the steps between feed settings on the machine were not suitably matched with the feeds required by the search. This problem was generally solved by slightly changing the required feeds to coincide with machine settings. However, it was found that the strategy employed to shrink the step size and test pattern when the search approached the optimum could not be feasibly implemented on the machine available. The smaller test point distance of .0015 resulting from shrinking the pattern generally could not be maintained on the feed settings of the lathe.

Stopping Criteria

Since a minimum cost search with no product requirement constraints incorporated into the index of performance will result in constantly increasing feed rates, the search did not reach an area of oscillation. Thus, a stopping strategy similar to that in the computer simulation is not of much use. A stopping strategy could be developed, if feed rate could be bounded to a range within machine capabilities and resulting in acceptable product. The range would depend mainly on surface finish requirements.

Search II (Figure 32)

The second search was undertaken in order to determine the effect of increasing test point pattern distance and step size. If successful, a larger test pattern would result in fewer steps to the optimum area and could possibly avoid the problem area between steps 4 and 6 on Search I. In addition, a larger test point distance might permit the use of the strategy of decreasing step size near the optimum. This strategy has been described in the computer simulation phase.

In Search II, the method of steepest descent was used with the objective of minimizing cost. Cost was evaluated by an index of performance which was based on a tool life criterion of .015 inch of flank wear and no surface finish penalty cost. The test point distance was 50 sfpm in the speed direction and .0050 ipr in the feed direction. Two replications were taken at each point.

Figure 32 shows the effect of increasing test point distance and step size. The search proceeded in the same direction as Search I and avoided much of the problem encountered in steps 4 through 6 of the first search. From the data taken in Phase III the second search using a point separation of 50 sfpm and .0050 ipr is much more efficient.

A difficulty in using a larger point spread is that the optimum when approached could be greatly overstepped. This cannot be determined by the searches performed in this stage of the research because of the nature of the index of performance used. As mentioned, a search based on an index without a penalty cost or other constraint will not oscillate around an area but continue to increase feed in search of the optimum. However, the matter can be examined in the computer simulation. Adequate testing at different starting points could reveal which point separation results in a more efficient search but this question would have to be resolved for many machining examples before a conclusion is reached. From the results of the first and second search, it can be said that both separations tested offer satisfactory results with a spread of 50 sfpm and .0050 ipr having an advantage in efficiency for this particular case.

Conclusions

1. A self-adaptive procedure based on the method of steepest descent search technique was found to be capable of determining cutting conditions which were economically superior to conditions recommended in Machinability Handbooks. Proper application of such a procedure would be in a long-running operation of economic significance and of a reasonable cutting time duration.

2. The method of steepest descent using an index of performance of minimum cost per piece or per cubic inch of material removed performs a satisfactory search when a 4 point test point pattern was used. A point separation of 30 sfpm and .003 ipr or 50 sfpm and .005 ipr is adequate for the searches in turning operations.

3. Replications at the test points are required due to substantial machining variation. Two repetitions were found to provide reliable search information for the machining performed in the laboratory. For actual production, the search may require two to four replications if variability is more pronounced.

4. The starting point cutting conditions were observed to have little effect on the final results of the search.

5. To prevent persistent overstepping of the optimum, some means must be built into the search to decrease step size as the optimum is approached and to stop the search when continued operation would not provide reasonable improvement. The techniques described to perform those functions were very satisfactory in the computer simulation but difficult to apply in actual machining situations.

6. The computer simulation search offered a good means of testing various stategies. The machining verification phase showed that such a search method as developed in the computer simulation model, was feasible and practical. The computer simulation found that the use of an index of performance incorporating a surface finish penalty cost produced good results. Difficulty was found in applying the same index to a machining situation possibly due to wider variability found in the machine shop case.

Summary and Recommendations for Future Study

From the results of the three phases of the research, it can be seen that a self-adaptive procedure based on optimum-seeking search technique can be valuable in improving handbook recommended cutting conditions for a particular operation. Improvement of cutting conditions has direct and favorable economic consequences which are often overlooked. The implementation of a self-adaptive procedure would be somewhat costly but much less expensive than modern adaptive control equipment. As with adaptive control, self-adaptive techniques are not applicable to all operations but can be successfully used in cases of long cutting duration and of substantial economic importance. The cost of implementation would be mainly in data collection and analysis.

This research does not intend to offer the best search strategy to improve cutting conditions. It is questionable whether a best strategy exists for all machining situations. However, the study demonstrates that such a strategy can substantially improve the economics and productivity of metal machining. Future work should concentrate on the applications of a search strategy to real machining situations. The mechanics of the strategy may very well be different for each case due to different management objectives and widely varying shop conditions, but it is believed that a self-adaptive strategy can be successfully applied to production environments.

APPENDIX

APPENDIX A1

Derivation of Equation for Minimum Cost Cutting Speed

The basic model for cost per piece is

$$C_u = C_o t_m + \frac{t_m}{T}(C_o t_c + C_t) + C_o t_h$$

The machining time is

$$t_m = \frac{L}{f\,N} = \frac{L\,\pi\,D}{12fV}$$

Assuming Taylor tool life equation is valid, the substitution can be made

$$C_u = C_o\,\frac{L\,\pi\,D}{12\,fV} + \frac{\frac{L\,\pi\,D}{12fV}}{\frac{C^{1/n}}{V^{1/n}}}(C_o t_c + C_t) + C_o t_h$$

For simplification let:

$$A = \frac{L\,\pi\,D}{12fV}$$

The model is therfore

$$C_u = C_o A V^{-1} + \frac{AV^{1/n-1}}{C^{1/n}}(C_o t_c + C_t) + C_o t_h$$

Taking the derivative with respect to speed and equating the derivative to zero permits the minimum point to be determined.

$$\frac{dC_u}{dV} = -C_o A V_{min}^{-2} + (1/n-1)\frac{AV_{min}^{1/n-2}}{C^{1/n}}(C_o t_c + C_t) = 0$$

Dividing through by $A \times C_o$ and rearranging

$$V_{min}^{-2} = \frac{V^{1/n-2}\,(1/n-1)}{C^{1/n}} \quad \frac{(C_o t_c + C_t)}{C_o}$$

Multiplying both sides by V_{min}^{2}

$$1 = \frac{V_{min}^{1/n}\,(1/n-1)}{C^{1/n}} \quad \frac{C_o t_c + C_t}{C_o}$$

Separating $V_{min}^{1/n}$ yields

$$V_{min}^{1/n} = \frac{C^{1/n}}{\left[1/n - 1\right]\left[\frac{C_o t_o + C_t}{C_o}\right]}$$

Raising both sides to the n power

$$V_{min} = \frac{C}{\left[\left(\frac{1}{n} - 1\right)\left(\frac{C_o t_c + C_t}{C_o}\right)\right]^{n}}$$

Derivation from DeVries, pp. 17- 8.

APPENDIX A2

For a speed-feed tool life model:

$$VT^n f^m = C \tag{1}$$

and solving for T:

$$T = C^{1/n} V^{-1/n} f^{m/n} \tag{2}$$

The cost per unit equation is:

$$C_u = C_o \left[t_h + t_m \, (1 + R/T) \right]$$

where:

$$R = t_c + C_t/C_o$$

$$t_m = \frac{L \pi D}{12fV}$$

Assuming Taylor tool life equation is valid, the substitution can be made into the cost equation:

$$C_u = C_o \left[t_h + \frac{L \pi D}{12fV} \left(1 + RC^{-1/n} V^{1/n} f^{m/n} \right) \right]$$

To determine the optimum speed, V*, and feed, f*, the partial derivative of the cost equation with respect to each of the two variables is set equal to zero.

For speed:

$$\frac{dC_u}{dV} = 0 = C_o \left[0 + \frac{L \pi D}{12 \, fV} \left(\frac{R}{n} C^{-1/n} V^{(1/n-1)} f^{m/n} \right) - \left(1 + RC^{-1/n} V^{1/n} f^{m/n} \right) L \pi \, D/12fV^2 \right]$$

or inserting equation (2)

$$R/nT^* = 1 + R/T^*$$

and therefore, $T^* = R(1/n - 1)$ (3)

where the value of T^* is the tool life which will result in minimum cost when V is varied.

If partial derivative with respect to feed is taken we find that

$$T^* = R\,(m/n - 1) \qquad (4)$$

Equations (3) and (4) can only be simultaneously satisfied if $m = 1$. If we refer to equation (2) it can be seen that if $m = 1$, then tool life would vary as much with feed as with speed. This is generally not true.

Derivation from N. Cook, Manufacturing Analysis, p. 160-1.

APPENDIX B1

TABLE 1

WORK DIAMETER SUMMARY

OBS. NO.	V	f	DIAM.	HARDNESS A	HARDNESS B
1	200	.0300	5.10	36.30	35.42
2	300	.0256	5.10	36.30	35.42
3	600	.0051	4.95	36.13	35.23
4	500	.0147	4.95	36.13	35.23
5	200	.0204	4.95	36.13	35.23
6	300	.0147	4.80	35.85	34.92
7	400	.0102	4.60	35.47	34.56
8	500	.0051	4.60	35.47	34.56
9	400	.0204	4.60	35.47	34.56
10	600	.0147	4.45	35.20	34.28
11	300	.0102	4.45	35.20	34.28
12	500	.0250	4.45	35.20	34.28
13	500	.0147	4.45	35.20	34.28
14	400	.0204	4.45	35.20	34.28
15	300	.0256	4.15	34.70	33.75
16	600	.0102	4.15	34.70	33.75
			4.00	34.50	33.48

V = speed in SFPM
f = feed in IPR
DIAM. = work diameter in IN.

HARDNESS = work hardness in R_C
A = max. hardness
B = min. hardness

APPENDIX B2

Equipment and Instrumentation

1. LeBlond 16 inch Heavy Duty Engine Lathe, The R. K. LeBlond Machine Tool Company.
2. Varidyne Control Unit, U.S. Electrical Motors.
3. Toolmaker's Microscope - Type 33 - 14 - 06 Bausch and Lamb Optical Co.
4. Jagabi Speed Indicator (Tachometer) - Cat. #9911, James G. Biddle Co.
5. Tachometer - TK - 24, Stewart Warner Company.
6. Surfindicator, Brush Instruments.
7. Planimeter, Keuffel and Esser.
8. Optical Comparator.

APPENDIX B3

TABLE I

For flank wear data summary refer to Data File held by Dr. Mikell P. Groover of the Department of Industrial Engineering.

APPENDIX B3

TABLE II

For crater wear summary
refer to Data File held
by Dr. Mikell P. Groover
of the Industrial Engi-
neering Department.

APPENDIX B3

TABLE III

For surface roughness data summary refer to Data File held by Dr. Mikell P. Groover of the Department of Industrial Engineering.

APPENDIX B4

TABLE I

FLANK WEAR MODEL

MODEL FORM: $FW = FW_o + FWR \times t$

FW	Flank wear Estimate in inches
FW_o	Initial or Break-in Flank wear estimate in inches
FWR	Flank Wear Rate Estimate in inches/min.
t	Time in minutes

FW_o can be modelled as follows:

$$FW_o = DV^n f^m$$

	D	Constant: .000147462990
	V	Speed in SFPM
	f	Feed rate in IPR
	n	Constant: 1.9533037458
	m	Constant: 1.7814053448
For Model:	Se	Std. Error of Est: .394126
	R	.9014

FWR can be modelled as follows:

$$FWR = EV^r f^q$$

E	Constant: .000000048812
V	Speed in SFPM
f	Feed rate in IPR
r	Constant: 2.9949660718
q	Constant: 1.5655362594

For Model: Se Std. Error of Est.: .442034 R = .8857

APPENDIX B4

TABLE II

CRATER WEAR MODEL

MODEL FORM: $CW = CW_o + CWR \times t$

CW	Crater Wear Estimate in inches ^{2}
CW_o	Initial of Break-in Crater Wear Estimate in inches^2
CWR	Crater Wear Rate Estimate in inches^2/min.
t	Time in minutes

CW_o can be modelled as follows:

$$CW_o = FV^x f^w$$

F	Constant: .003851933
V	Speed in SFPM
f	Feed rate in IPR
x	Constant: .5851220973
w	Constant: .9529752416

For Model: Se Std Error of Est: .21167
R .9073

CWR can be modelled as follows:

$$CWR = GV^z f^y$$

G	Constant: .000000090
V	Speed in SFPM
f	Feed rate in IPR
z	Constant: 2.1778405883
y	Constant: .9980432617

For Model: Se Std. Error of Est: .443038
R .8172

APPENDIX B4

TABLE III

SURFACE ROUGHNESS MODEL

MODEL FORM: $SF = (CV^a f^b FW^c)$

SF	Surface Roughness Estimate in microinches
C	Constant: 1.0104487460×10^5
V	Speed in SFPM
f	Feed rate in IPR
FW	Flank Wear in inches
a	Constant: -.3929000000
b	Constant: .8183500000
c	Constant: .2122000000

For Model: Se .31928
R .89322

APPENDIX C

TABLE I

SEARCH I

Step No.	Speed (sfpm)	Feed (ipr)
1	300	.0152
2	275	.0176
3	275	.0204
4	245	.0204
5	265	.0176
6	270	.0204
7	250	.0224
8	270	.0256
	250	.0256

APPENDIX C

TABLE II

SEARCH II

Step No.	Speed (sfpm)	Feed (ipr)
Start	300	.0152
1	270	.0204
2	225	.0224
3	300	.0224
4	225	.0256

Bibliography

1. American Society for Metals, Metals Handbook, Volume 3, Machining, Metals Park, Ohio, 1967.

2. Armarego, E. J. A. and J. K. Russell, "Maximum Profit Rate as a Criterion for the Selection of Machining Conditions," International Journal of Machine Tool Design and Research, Vol. 6 (1966), p. 15.

3. Bhattacharyya, A. and I. Ham "Analysis of Tool Wear - Part I- Theoretical Models of Flank Wear", Trans. ASME, Journal of Engineering for Industry, Vol. 91, No. 3, 1969, p. 790.

4. Bhattacharyya, A. and I. Ham, "Analysis of Tool Wear- Part II - Applications of Flank Wear," Trans. ASME, Journal of Engineering for Industry, Vol. 92, No. 1, 1970, p. 109.

5. Box, G.E.P. and N.R. Draper, Evolutionary Operation, New York, John Wiley and Sons, Inc., 1969.

6. Cook, N.H., Manufacuturing Analysis, Reading, Mass., Addision-Wesley Publishing Co., 1966.

7. Crookall, J.R., "The Performance Envelope Concept in the Economics of Machining," International Journal of Machine Tool Design and Research, Vol. 9, No. 3, 1969, p. 261.

8. DeVries, M.F., "Machining Economics - A Review of the Traditional Approaches and Introduction to New Concepts", SME Tech. Paper MR69-279, 1969.

9. Eveleigh, V.W., Adaptive Control and Optimization Techniques, New York, McGraw-Hill, Inc., 1967.

10. Gilbert, W.W., "Economics of Machining," Machining Theory and Practice, Cleveland, Ohio, American Society for Metals, 1950.

11. Groover, M.P. and R. J. Johnson, "Alternative Methods for Determining Optimum Machining Conditions," SME Tech. Paper No. MR74-703, 1974.

12. Groover, M.P. and R. J. Johnson, "The Application of a Machining Process Model," AIIE Proceedings, 1974, pp. 261-8.

13. Groover, M.P., "Computer Simulation of the Machining Economic Problem - Part I: Tool Wear and Surface Finish Models," (Unpublished), Lehigh University, 1973.

14. Groover, M.P., "Computer Simulation of the Machining Economics Problem - Part II: Determining Optimum Cutting Conditions", (Unpublished), Lehigh University.

15. Groover, M.P., "A Definition and Survey of Adaptive Control Machining," SME Tech. Paper No. MS70-561, 1970.

16. Ham, Inyong, "Computer Optimization of Machining Conditions for Shop Production," U.S. Army Weapons Command Tech. Report No. SWERR-TR-72-73, October, 1972.

17. Johnson, R. J., "The Application of Adaptive Control in the Implementation of a Machinability Data System," (Unpublished), Lehigh University, 1974.

18. Lambert, B.K., and K. Taraman, "Development and Utilization of a Mathematical Model of a Turning Operation," International Journal of Machine Tool Design and Research, Vol. 11, No. 1, 1973, pp. 69-91.

19. Parsons, N. R. ed., N/C Machinability Data Systems, Dearborn, Michigan, Society of Manufacturing Engineers, 1971.

20. Porter, B. and R.D.M.J. Summers, "The Performance of Self-Optimalizing Strategies in the Adaptive Control of the Metal Cutting Processes, " International Journal of Machine Tool Design and Research, Vol. 8, No. 4, 1968, p. 217.

21. Society of Manufacturing Engineers, Tool Engineers Handbook, New York, McGraw-Hill Inc., 1959.

22. Taylor J., "The Tool Wear Time Relationship in Metal Cutting," International Journal of Machine Tool Design and Research, Vol. 2, 1962, pp. 119-52.

23. Vidosic, J.P., Metal Machining and Forming Technology, New York, The Ronald Press Co., 1964.

24. Wu, S.M. and D.S. Ermer, "Maximum Profit as the Criterion in Determination of Optimum Cutting Conditions", Trans., ASME Journal of Engineering for Industry, Vol. 88, (1966), p. 435.

Vita

The author was born in Abington, Pennsylvania on January 10, 1952, the son of James R. and Mary C. Johnson.

He attended secondary school in Oreland, Pennsylvania and received his high school diploma from Springfield Township High School in June, 1969. He continued his studies at Lehigh University, where he received the degree of Bachelor of Science in Industrial Engineering in June, 1973. Following graduation, he worked as a research assistant under a National Science Foundation contract while studying for the Master of Science in Industrial Engineering.